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- (71) Applicant (*for all designated States except US*): **THE TRUSTEES OF COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK** [US/US]; 116th Street and Broadway, New York, NY 10027 (US).
- (72) Inventors; and
- (75) Inventors/Applicants (*for US only*): **KALIFA, Jerome** [FR/US]; 184 Thompson Street, New York, NY 10012 (US). **LAINE, Andrew** [US/US]; 39 Claremont Avenue, Apartment 72, New York, NY 10027 (US). **ESSER, Peter, D.** [US/US]; 37 Cambridge Drive, Smithtown, NY 11787 (US).
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(54) Title: **METHOD FOR TOMOGRAPHIC RECONSTRUCTION WITH NON-LINEAR DIAGONAL ESTIMATORS**

(57) Abstract: Techniques for tomographic reconstruction using non-linear diagonal estimators are disclosed. In a preferred embodiment, tomographic data from a tomographic device is decomposed in a wavelet vector family. Regularization of the tomographic data is accomplished by performing a thresholding operation on coefficients of the decomposed data. The regularized data is reconstructed into image data that may be displayed. In another preferred embodiment, a wavelet packet vector family is used to decompose the tomographic data. The wavelet packet is selected from a dictionary of wavelet packets using the best basis algorithm.

METHOD FOR TOMOGRAPHIC RECONSTRUCTION WITH NON-LINEAR DIAGONAL ESTIMATORS

SPECIFICATION

RELATED APPLICATION

5 This application claims priority from U.S. provisional application Nos. 60/201,679 and 60/222,871 filed on April 28, 2000 and August 3, 2000 respectively, which are both incorporated herein in their entirety.

BACKGROUND OF INVENTION

10 Computerized tomography has been used for many years, especially in the area of medical imaging, for providing nondestructive or noninvasive techniques for generating sectional views of an object. A good description of such systems appears in U.S. Patent No. 5,414,622, which is incorporated herein by reference. These imaging systems measure the density or metabolic activity of a section of the observed object (such as a patient's body) and produce raw acquisition data. This
15 acquisition data consists of tomographic projections or is processed to obtain tomographic projections, which may be used in a tomographic reconstruction procedure to obtain image data associated with a sectional view of the observed object. These techniques are presently employed in medical imaging systems such as X-ray computerized tomography (CT) systems, positron emission tomography (PET)
20 systems and Single Positron Emission Computerized Tomography (SPECT) systems. Applications in fields other than medical imaging include seismology and geophysical sciences where ground penetrating acoustic radiation is employed and reflected signals are processed to obtain tomographic projections of sub-surface structures. Other applications will be apparent to one skilled in the art.

25 These systems can be described mathematically as follows. A section of the object to be observed by the tomographic device is represented by an image $f_c(x_1, x_2)$, where x_1 and x_2 are the spatial dimensions of the image. In the discrete case, f is an image matrix with $N_1 \times N_2$ elements and each member of f includes pixel information such as, grayscale value or brightness. An estimation of f is derived by a

tomographic reconstruction procedure from the tomographic projections of f , denoted $Y[t, \alpha]$, and defined as:

$$Y[t, \alpha] = Rf[t, \alpha] + W[t, \alpha] \quad (\text{Eq. 1})$$

where W is an additive noise, R is the discrete Radon transform, which
 5 models the tomographic projection process, α is the angle of projection and t is the position on the line integral. The discrete Radon transform is derived from its continuous version R_c , which is equivalent to the X-ray transform in two dimensions described in S.R. Deans, *The Radon Transform And Some Of Its Applications* (John Wiley and Sons) (1983) and expressed as

$$10 \quad (R_c f_c)(t, \alpha) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_c(x_1, x_2) \delta(x_1 \cos \alpha + x_2 \sin \alpha - t) dx_1 dx_2 \quad (\text{Eq. 2})$$

where f_c is a square integrable function δ is the Dirac mass function where $\delta(x)=1$ when $x=0$ and $\delta(x)=0$ otherwise and α is an angle from 0 to 2π radians. Figure 5 is a diagram showing a typical relationship between R, f, t and α .

One skilled in the art will recognize that there are several ways to
 15 define the discrete Radon transform based on the continuous Radon transform. Some of those methods are described in P. Toft, *The Radon Transform and Implementation*, Ph.D. thesis, Department of Mathematical Modeling, Technical University of Denmark (1996). Typically, a line integral along $x_1 \cos \alpha + x_2 \sin \alpha = t$ is approximated by a summation of the pixel values inside the strip $t-1/2 \leq n_1 \cos \alpha + n_2 \sin \alpha \leq t + 1/2$.
 20

The noise W from Eq. 1 is traditionally modeled as Gaussian or Poisson noise. However, since the tomographic projections Y are often processed to incorporate various corrections, such as attenuation correction, scatter correction, resolution correction and geometric correction, the resulting noise W does not actually
 25 comply with such statistical models.

Once tomographic projections are obtained, reconstruction of the desired image data proceeds in two steps. The steps may be performed in either order. The first of these steps is backprojection. This step entails computing the inverse radon transform (R^{-1}) of the tomographic projections Y . A discrete backprojection
 30 may be directly computed by (a) radial interpolation, using techniques well known to

one skilled in the art and (b) deconvolution to amplify the high frequency components of the 1-dimensional Fourier transforms of Y in the direction of t by multiplying the 1-dimensional Fourier transforms of Y in the direction of t by a high-pass filter, such as a ramp filter.

- 5 Second, regularization is performed. It follows from Eq. 1 that computing the inverse Radon transform of the tomographic projections yields:

$$R^{-1}(Y) = f + R^{-1}(W), \quad (\text{Eq. 3})$$

- Where the desired image f is contaminated by additive noise $R^{-1}(W)$. Because the Radon transform R is a smoothing transform, computing its inverse R^{-1} in the presence of additive noise W is an ill-posed inverse problem, so $R^{-1}(W)$ represents
10 a large additive noise. Consequently, the regularization step is necessary to remove as much of the additive noise as possible from the final reconstructed data.

- The prior art teaches two approaches to regularization, both of which suffer shortcomings. The most popular regularization technique in the prior art is
15 known as Filtered Back-Projection (FBP). FBP and its derivatives are linear filtering techniques in the Fourier space. FBP suffers from limitations due to the fact that the vectors of the Fourier basis are not adapted to represent spatially inhomogeneous data typically found in images. The second well-known technique for regularization utilize iterative statistical models (ISM) designed to implement Expectation-
20 Maximum (EM) and Maximum A Posteriori (MAP) estimators. These techniques are described in G. McLachlan and T. Krishnan, *The EM Algorithm and Extensions* (New York: Wiley) (1997) and L.A. Shepp and Y. Vardi, *Maximum Likelihood Reconstruction For Emission Tomography*, Transactions on Medical Imaging, 1982, at 113-122. Although ISM methods can show an improvement over FBP techniques,
25 they suffer from several drawbacks, including long computation times, lack of theoretical understanding to characterize estimation error and convergence problems.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide improved methods for regularization of tomographic projection data.

In one embodiment of the present invention, a method is provided for reconstructing image data corresponding to a cross-section of an object, such as a patient. Tomographic projection data supplied by a tomographic device is backprojected. The backprojected data is decomposed in a wavelet or wavelet packet
5 vector family. The decomposed data is then diagonally operated upon and the modified data is then recomposed to form image data corresponding to the desired image by inverting the wavelet vector decomposition. In a highly preferred embodiment, the diagonal operation consists of thresholding the decomposed data to attenuate or eliminate certain decomposition coefficients.

10 In another preferred embodiment of the present invention, the supplied tomographic projection data is first decomposed in a wavelet or wavelet packet vector family. The decomposed data is then diagonally operated upon. Next, the data is recomposed by inverting the wavelet vector decomposition. Finally, the data is backprojected to form image data corresponding to the desired image.

15 In another embodiment, the supplied tomographic data is decomposed and diagonally operated upon as described above. The data is then selectively amplified to approximate the deconvolution step of backprojecting the data. The data is then recomposed by inverting the wavelet vector decomposition and the resulting data is radially interpolated to form image data corresponding to the desired image.

20 In a further embodiment, the selective amplification can occur before the diagonally operating step.

In a highly preferred embodiment, the wavelet or wavelet packet vector family chosen to decompose the tomographic data is a wavelet packet family. A dictionary of wavelet packet decompositions to choose is provided. One of those
25 decompositions is selected by calculating an estimation of final estimation error based on the selected wavelet packet decomposition and a model of the noise in the tomographic projection data for each possible wavelet packet decomposition and choosing the wavelet packet decomposition with the minimum estimated estimation error. In another preferred embodiment, the model of the noise in the tomographic
30 projection data is extracted from the tomographic projection data. In yet another preferred embodiment, prior information about the desired image gained from

analysis of previous similar images, e.g. of "phantoms", is used to calculate the estimated estimation error.

In another preferred embodiment, tomographic information corresponding to multiple cross-sections of an object, such as a patient, is provided
5 and the desired image is reconstructed using all of the supplied data.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a flow diagram of one embodiment of a method according to the present invention.

Figure 2 shows a flow diagram of another embodiment of a method
10 according to the present invention.

Figure 3 shows a flow diagram of another embodiment of a method according to the present invention.

Figure 4 shows a flow diagram of a preferred wavelet family selection step useful in the methods of Figures 1-3.

Figure 5 shows a conceptual relationship between an object to be
15 imaged and a portion of its Radon transform.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIEMENTS

Figure 1 shows one method of implementing the present invention. In step 101, tomographic data generated by a tomographic device such as an X-ray CT
20 scanner, PET or SPECT device is supplied and backprojected. The tomographic data may be raw, or may be pre-processed to correct for attenuation, scatter, resolution, geometric anomalies, etc. These pre-processing methods are well known to one skilled in the art. The backprojection step, as previously described, involves radially interpolating the data as well as deconvolving the data. Radial interpolation is well
25 known to one skilled in the art. In the preferred embodiment, linear interpolation is performed, however other radial interpolation techniques such as the nearest neighbor or spline radial interpolation algorithms can be utilized. Deconvolution is also well known to one skilled in the art and consists of multiplying the one dimensional Fourier transform of the projection data in the direction of t by multiplication by a
30 high-pass filter such as a ramp filter. The entire backprojecting step is described in

detail in U.S. Patent Nos. 5,778,038 and 5,414,622, incorporated herein by reference. Attached as Appendix A is a MATLAB™ code listing implementing one embodiment of the present invention. The backprojecting steps are performed during the function *filtback* in the code.

5 In step 103, a wavelet or wavelet packet vector family is selected to decompose the backprojected data. Either one-dimensional or two-dimensional wavelet vector families can be used. The wavelet or wavelet packet vector family can be an orthogonal basis, a biorthogonal basis or a complex or non-complex frame. A biorthogonal basis differs from an orthogonal basis in that the vector family used to
10 reconstruct the data (denoted g^* herein) is different than the vector family used to decompose the data (denoted g herein). Biorthogonal bases are preferable when particular properties of the wavelet vectors or wavelet packet vectors, such as support size, regularity, symmetry and number of vanishing moments are difficult or impossible to achieve using a orthogonal basis. Selection of a wavelet packet vector
15 family allows a more flexible and accurate segmentation of the frequency domain, as the supports of the Fourier transforms of the wavelet packets nearly segment the frequency space. Complex wavelet frames and complex wavelet packets are translation invariant transforms that generate complex coefficients. These vector families provide improved directional selectivity. All of these vector families will be
20 known to one skilled in the art and are described in S. Mallat, A Wavelet Tour of Signal Processing (Academic Press, 2d Ed.) 1999. The chosen vector family is denoted B herein. In a preferred embodiment demonstrated by the code in Appendix A, a two dimensional wavelet packet decomposition based on the Symmlet wavelet is used.

25 Referring to Figure 4, a highly preferred embodiment of the vector family selection step 103, where the vector family chosen is a one or two dimensional wavelet packet frame, will be described. The function *SPECTMacrTomoFiltback* in the MATLAB™ code listing contained in Appendix A implements the steps involved in the embodiment illustrated in Figure 4 using a two dimensional wavelet packet
30 frame and provides further description of the steps illustrated in Figure 4. In step 401, a model of the noise in the tomographic projection data is derived. The model may be

predetermined, or it may be determined from information extracted from the tomographic projection data. A dictionary of potential wavelet packet decompositions is also supplied. Generating the dictionary of wavelet packet decompositions is well known to one skilled in the art. In step 403, a possible wavelet packet decomposition is selected from the supplied dictionary. In step 405, an estimation of the final estimation error of the reconstructed image based on the selected wavelet packet decomposition and noise model is calculated. In step 407, the process repeats from step 403 if other potential wavelet packet decompositions in the supplied dictionary remain to be analyzed.

10 In step 409, the wavelet packet decomposition that minimizes estimated final estimation error is chosen.

An algorithm for selecting the wavelet packet which minimizes the estimated final error as shown in steps 405 and 409 is well known in the art and is described in R. Coifman and M. Wickerhauser, *Entropy-Based Algorithms for Best Basis Selection*, 38 IEEE Trans. Info. Theory, 713 (Mar. 1992) and in U.S. Patent Nos. 5,526,299 and 5,384,725 which are incorporated by reference herein. Generating a criterion to employ in implementing the algorithm of Coifman and Wickerhauser that estimates the estimation error based on a model on the noise in the tomographic projection data is well known to one skilled in the art and is described in S. Mallat, *A Wavelet Tour of Signal Processing* (Academic Press 2d Ed.) (1999). Although not shown in Figure 4, as noted in the code listing of Appendix A, the criterion can be based on information about the image to be observed in addition to information about the noise in the tomographic projection data by making reference to a prior observation, e.g. of a "phantom", of an object similar to the object under investigation.

25 Returning to Figure 1, in step 105, the backprojected tomographic data is decomposed into vector family *B*. The algorithms employed to decompose the data are well known to one skilled in the art and will depend on the vector family chosen. In the preferred embodiment implemented in the code listing of Appendix A, a fast filter-bank transform is used. A fast lifting scheme may also be employed. Fast filter bank transforms are well known to one skilled in the art and are described in S.

Mallat, *supra*. Lifting schemes are also well known to one skilled in the art and are described in W. Sweldens, *The lifting Scheme: A Construction of Second Generation Wavelets*, 29 SIAM J. of Math. Analysis 511, 546 (1997). Techniques for decomposing in other wavelet vector families, using other filter bank techniques such as translation averaging are also possible.

In step 107, the decomposed data is diagonally operated on. This step consists of multiplying the decomposed data coefficient by a scalar value ρ_i . In a preferred embodiment, ρ_i is a thresholding operator T_i , defined:

$$\rho_i(x) = \begin{cases} x & \text{if } |x| > T_i \\ 0 & \text{if } |x| \leq T_i \end{cases}, \text{ or} \quad (\text{Eq. 4})$$

$$\rho_i(x) = \begin{cases} x - T_i & \text{if } x \geq T_i \\ x + T_i & \text{if } x \leq -T_i \\ 0 & \text{if } |x| < T_i \end{cases}, \text{ or} \quad (\text{Eq. 5})$$

$$\rho_i(x) = \begin{cases} x & \text{if } |x| \geq T_i \\ \text{sign}(x)(\lambda|x| - T_i) & \text{if } T_i\left(1 - \frac{1}{\lambda}\right) < |x| < T_i \\ 0 & \text{if } |x| \leq T_i\left(1 - \frac{1}{\lambda}\right) \end{cases}, \quad (\text{Eq. 6})$$

where $\lambda > 1$, or using a sigmoid function. Eq. 4 describes a soft-thresholding operator, Eq. 5 describes a hard thresholding operator, and Eq. 6 describes a "piece-wise affine" thresholding operator. T (and in the case of piece wise affine thresholding, λ) is chosen to minimize a numerical measure of error, or to satisfy perceptual requirements according to the needs of the person or device that will interpret the reconstructed image. In a typical case, λ is 1/2 and T is three times the estimated standard deviation of the noise in the tomographic data.

Finally, in step 109, the data is recomposed using the inverse decomposition of the wavelet or wavelet packet vector family decomposition performed in step 105. The inverse decomposition process will be known to one skilled in the art and is based on the same techniques utilized in step 105. Thus,

where the forward transform utilizes filter bank techniques, the reverse transform uses the same techniques. In the preferred embodiment implemented in the code listing of Appendix A, an inverse transform using a filter bank is employed. The resultant data is image data corresponding to the desired cross-sectional image which may viewed or printed using an apparatus well known to one skilled in the art.

A mathematical representation of the steps performed in steps 101 through 109 follows. Let $B = \{g_i, g_i^*\}_{0 \leq i \leq M}$ with $M \geq N_1 \times N_2 - 1$ be the vector family (previously described) in which the regularization of the data is computed where $\{g_i^*\}_i$ is the dual family of the family of vectors $\{g_i\}_i$, used during the reconstruction process. When $\{g_i\}_i$ is an orthogonal basis, the families g and g^* are identical. The diagonal estimator F (which is the matrix of regularized image data) of f is expressed:

$$F = \sum_i \rho_i \left(\langle R^{-1}Y, g_i \rangle \right) g_i^* . \quad (\text{Eq. 7})$$

Figure 2 illustrates a slightly modified version of the embodiment described with reference to Figure 1. In the embodiment of Figure 2, the step of backprojecting the data 209 occurs last. The backprojection step 209 is identical to backprojection step 101 shown in Figure 1 in all other respects. The remaining steps shown in Figure 2 are also identical to the corresponding steps shown in Figure 1. Thus, step 201 corresponds to step 103. Step 203 corresponds to step 105. Step 205 corresponds to step 107. Step 207 corresponds to step 109. Accordingly, unlike the embodiment illustrated in Figure 1, the regularization process performed in steps 201 through 207 occurs before application of the inverse operator R^{-1} .

A mathematical representation of the steps performed in steps 201 through 209 follows. Let $B = \{g_i, g_i^*\}_{0 \leq i \leq M}$ with $M \geq N_1 \times N_2 - 1$ be the vector family in which the regularization of the data is computed. The diagonal estimator F of f is expressed:

$$F = R^{-1} \left(\sum_i \rho_i \left(\langle Y, g_i \rangle \right) g_i^* \right) . \quad (\text{Eq. 8})$$

Figure 3 illustrates another embodiment of the present invention, where the process of backprojecting the tomographic data is partially performed during the regularization process. In step 301, a wavelet packet vector family is

selected for decomposition of supplied tomographic data. The process is similar to that described above with reference to step 103 in Figure 1, except that this embodiment requires the use of a wavelet packet or complex wavelet packet frame as the selected vector family.

5 In step 303, the tomographic data is decomposed using a similar process as described with reference to step 105 in Figure 1.

 In step 305, the data is diagonally operated on in a process similar to that described with reference to step 107 in Figure 1.

 In step 307, the data is selectively amplified. This step consists of
10 amplifying selected wavelet packet coefficients to approximate amplification of the high frequency components of the tomographic projection data. In accordance with this embodiment, it is unnecessary to perform a Fourier transform and its inverse to backproject the tomographic projection data, rather all that is required in addition to the amplification step is radial interpolation described below. Selection of wavelet
15 packet coefficients to amplify in order to approximate the traditional deconvolution step of backprojection will be apparent to one of skill in the art. In a preferred embodiment, each wavelet packet vector has a frequency support which is mostly concentrated on a band of the Fourier domain. In other words, the supports of the Fourier transforms of the various wavelet packets approximately segment the Fourier
20 domain. The deconvolution by a ramp filter function is then approximated by amplifying the coefficients in the wavelet packet space by a value that is the mean value of the ramp filter function on the support of the corresponding wavelet packet vector.

 In step 309, the data is recomposed using the inverse decomposition of
25 the wavelet packet decomposition performed in step 303. The process is similar to that described with respect to step 109 in Figure 1.

 Finally, in step 311, the data is radially interpolated to complete backprojection. This step is well known to one skilled in the art and is discussed above with respect to step 101.

As symbolized by arrow 306, the steps of diagonally operating 305 and selectively amplifying data 307 can occur in either order. In other words, step 307 may be performed before step 305.

The embodiments described above could also be combined to improve regularization of the tomographic data. For instance, the embodiment of Figure 2 could be combined with the embodiment of Figure 1, beginning with step 201, proceeding through Figure 2 to step 209 then moving to step 103 of Figure 1 and proceeding to step 109. In such an instance, the same decomposition vector family *B* could be used, or two different vector families could be selected during steps 201 and 103.

Additionally, the invention is intended to include regularization of three-dimensional image data in addition to traditional two-dimensional cross-section images. In a three dimensional embodiment of the present invention, a series of tomographic projections of two-dimensional cross-sectional slices of the observed object are provided by a tomographic device. The complete three-dimensional data set is then operated upon, which has the effect of better discriminating between desired information and additive noise.

An example of a three-dimensional embodiment of the present invention is now described with reference to Figure 1. In step 101, data corresponding to tomographic projections of a series of cross-sectional slices of the observed object are provided and the projections are backprojected for each cross-sectional slice, generating data corresponding to a series of noisy cross-sectional slices of the observed object. The backprojection step for each cross-sectional slice is identical to that previously described with respect to Figure 1 in the two-dimensional embodiment.

Although not shown in Figure 1, it is advantageous that a two-dimensional regularization on each backprojected slice be performed using one of the embodiments previously described before proceeding to step 103.

In step 103, a wavelet or wavelet packet vector family is chosen to decompose the three dimensional data. Either one-dimensional, two-dimensional or three-dimensional wavelet vector families can be used. The wavelet or wavelet

packet vector family can be an orthogonal basis, a biorthogonal basis or a complex or non-complex frame. The chosen vector family is denoted B herein.

In step 105, the data is decomposed in the selected vector family. The step is similar to that previously described in the two-dimensional situation. In a highly preferred embodiment, a three-dimensional dyadic wavelet basis is chosen and the "a trous algorithm" is used to compute the decomposition. This algorithm is another method of performing a translation invariant decomposition and, like translation averaging, is a refinement of the filter bank decompositions previously discussed, although it is implemented differently than the translation averaging technique. The algorithm is an "undecimated" modification of the filter bank algorithm, without subsampling between each wavelet scale. The "a trous algorithm" is well known to one skilled in the art and is described in Mallet *supra*. An implementation of the "a trous algorithm" in MATLAB code is presented Appendix B.

In step 107, the data is diagonally operated upon using a process similar to that discussed in the two-dimensional embodiment. In a preferred embodiment, where a three-dimensional dyadic wavelet basis is chosen to decompose the backprojected data, the diagonal operation consists of thresholding the wavelet modulus. Specifically, the dyadic transform is computed with a family of discretized translations and dilations of three wavelets ψ^1 , ψ^2 and ψ^3 that are the partial derivatives of a smoothing function ϕ . Smoothing functions suitable for this purpose are well known to one skilled in the art and are discussed in Mallet *supra*. A typical smoothing function is a quadratic spline. Thus:

$$\psi^1(x_1, x_2, x_3) = \frac{\partial \phi(x_1, x_2, x_3)}{\partial x_1}, \quad \psi^2(x_1, x_2, x_3) = \frac{\partial \phi(x_1, x_2, x_3)}{\partial x_2}, \quad \psi^3(x_1, x_2, x_3) = \frac{\partial \phi(x_1, x_2, x_3)}{\partial x_3}$$

The three-dimensional vector family $\{g_i\}_i$ is then written $\{\psi_{jk}^k\}_{k=1,2,3,j}$. For a given j , the three wavelets have been equally dilated and are translated on the same position, but they respectively have a horizontal, vertical and axial direction.

The decomposed image f has three components which can be written as frame inner products, as:

$$T_j^k f = \langle f, \psi_j^k \rangle, \quad k = 1, 2, 3. \quad (\text{Eq. 9})$$

Because ψ^1 , ψ^2 and ψ^3 are partial derivatives of ϕ , these components are proportional to the coordinates of the gradient vector of f smoothed by a dilated version of ϕ . From these coordinates, a computation of the angle of the gradient
 5 vector is made, which indicates the direction in which the partial derivative of the smoothed image f has the largest amplitude. The amplitude of this maximum partial derivative is equal to the modulus of the gradient vector and is therefore proportional to the wavelet modulus, expressed as:

$$M_j f = \sqrt{|T_j^1 f|^2 + |T_j^2 f|^2 + |T_j^3 f|^2}. \quad (\text{Eq. 10})$$

10 Finally, thresholding of the modulus $M_j f$ is performed, rather than thresholding each wavelet transform component $T_j^k f$. This is equivalent to selecting a direction in which the partial derivative is a maximum and thresholding the amplitude of the partial derivative in this direction. This constitutes an adaptive choice of the wavelet direction in order to best correlate the signal. The coefficients of the dyadic
 15 wavelet decomposition are then computed back from the thresholded modulus and the angle of the gradient vector.

In step 109 the data is recomposed to generate a series of regularized cross-sectional slices.

A mathematical representation of the steps performed in steps 101
 20 through 109 for the situation with N_3 number of cross-sectional slices follows. Let $B = \{g_i, g_i^*\}_i$ be the vector family in which the regularization of the data is computed. The three-dimensional slice-by-slice backprojected data is:

$$\forall 0 \leq z \leq N_3 - 1 \quad X[.,., z] = R^{-1}(Y[.,., z]). \quad (\text{Eq. 11})$$

where z corresponds to the axial direction of the object under investigation. The
 25 diagonal estimator F of f is:

$$F = \sum_i \rho_i (\langle X, g_i \rangle) g_i^*. \quad (\text{Eq. 12})$$

It will be apparent to one skilled in the art that the embodiment illustrated in Figure 2 could be adapted in a similar manner to operate on three dimensional data as well. In that case, a mathematical representation of the steps

performed in steps 201 through 209 for the situation with N_3 number of cross-sectional slices follows. The regularized tomographic projection data is given by:

$$\tilde{Y} = \sum_i \rho_i \langle Y, g_i \rangle g_i^* \quad (\text{Eq. 13})$$

and the estimator F of f is:

$$5 \quad \forall 0 \leq z \leq N_3 - 1 \quad F = [.,., z] = R^{-1} \left(\tilde{Y}[.,., z] \right). \quad (\text{Eq. 14})$$

The foregoing merely illustrates the exemplary embodiments of the invention. Various modifications and alterations to the described embodiments will be apparent to those skilled in the art in view of the teachings herein. It will thus be fully appreciated that those skilled in the art will be able to devise numerous systems and methods which, although not explicitly shown or described, embody the principles of the invention and are thus within the spirit and scope of the invention, the scope of the invention being defined only by the appended claims.

10

APPENDIX A

```

function x = AffineThresh(y,t)
% AffineThresh -- Apply Affine Threshold
% Usage
5 %   x = AffineThresh(y,t)
% Inputs
%   y      Coeff before thresholding
%   t      Threshold
% Outputs
10 %   x      Thresholded coeff
%

        x = sign(y).*(abs(y) > t/2).*(abs(y) <= t).*(2*abs(y)-t) +
15 y .* (abs(y) > t);

% J.Kalifa, 2000

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```

function [basis,value] = Best2dBasis(sqtrees,D)
% Best2dBasis -- Coifman-Wickerhauser Best-2d-Basis Algorithm
20 % Usage
%   [btree,vtree] = Best2dBasis(sqtrees,D)
% Inputs
%   sqtrees  stat-quadtrees (output by Calc2dStatTree)
%   D        maximum depth of tree-search
25 % Outputs
%   btree    basis-quadtrees of best basis
%   vtree    value of components of best basis
%           vtree(1) holds value of best basis
%
30 % Description
%   The best-basis algorithm is used to pick out the ``best''
%   basis from all the possible bases in the packet table.
%   Here ``best'' means minimizing an additive measure of
%   information, called entropy by Coifman and Wickerhauser.
35 %
%   Once the stat-quadtrees of entropy values is created, Best2dBasis
%   selects the best basis using the pruning algorithm described in
%   Wickerhauser's book.
%
40 % Examples
%   % get best basis for ``image''
%   % use Coiflet 3 filter and CW Entropy
%   [n,D] = quadlength(image);
%   qmf = MakeONFilter('Coiflet',3);
45 %   sqtrees = Calc2dStatTree('WP',image,D,qmf,'Entropy');
%   [btree,vtree] = Best2dBasis(sqtrees,D);
%
% See Also
%   Calc2dStatTree, FPT2_CP, FPT2_WP
50 %
% References
%   Wickerhauser, M.V.  _Adapted_Wavelet_Analysis_.  AK Peters
%   (1994).
%
55 %
        global WLVERBOSE

```



```

        basis = zeros(size(sqrtree));
        value = sqrtree;
        for d=D-1:-1:0,
            for bx=0:(2^d-1),
                for by=0:(2^d-1),    % scan tree, bottom->top left->right
5          scan
                    vparent = sqrtree(qnode(d,bx,by));
                    vchild  = value(qnode(d+1,2*bx ,2*by)) + ...
10                  value(qnode(d+1,2*bx+1,2*by)) + ...
                    value(qnode(d+1,2*bx ,2*by+1)) + ...
                    value(qnode(d+1,2*bx+1,2*by+1));

                    if(vparent <= vchild), % if parent better than
15          children, RU486
                        basis(qnode(d,bx,by)) = 0;
                        value(qnode(d,bx,by)) = vparent;
                    else
20                  basis(qnode(d,bx,by)) = 1;
                        value(qnode(d,bx,by)) = vchild;
                    end
                end
            end
        end
25      if strcmp(WLVERBOSE,'Yes')
        fprintf('best basis %g \n',value(1))
        end

30      %
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      %

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40      %


---


function s = cyclespin2(x,i,j)

    [l1,l2] = size(x);
45    z = x((l1+1-i):l1,:);
    z(i+1:l1,:) = x(1:(l1-i),:);
    s = z(:,(l2+1-j):l2);
    s(:,j+1:l2) = z(:,1:(l2-j));

50    % Written by Maureen Clerc and Jerome Kalifa, 1997
    % clerc@cmapx.polytechnique.fr, kalifa@cmapx.polytechnique.fr



---


55    function [maxi,tree,T] = Dis2dStatTree(img,D,qmf,I,mult_sigma)

    [n,J] = quadlength(img);

```

```

boxlen = n;
boxcnt = 1;
coef = img;
coefI = I;
5   for d = 0:D,
    for bx=0:(boxcnt-1),
      for by=0:(boxcnt-1),
10      [lox,hix,loy,hiy] = quadbounds(d,bx,by,n);
      Quad = coef(lox:hix,loy:hiy);
      QuadI = coefI(lox:hix,loy:hiy);

      [s1,s2]=size(Quad);
15      %
      T_node=sqrt(4*log(n))*sqrt(1/(s1*s2)*sum(sum(QuadI.*QuadI)));
      T_node=mult_sigma*sqrt(1/(s1*s2)*sum(sum(QuadI.*QuadI)));
      r1= abs(Quad) < T_node;
      r2=1-r1;
20      p1=Quad.^2;
      pt1=p1.*r1;
      p2=QuadI.^2;
      pt2=p2.*r2;
      tree(qnode(d,bx,by)) = sum(sum(pt1))+sum(sum(pt2));
25      T(qnode(d,bx,by)) = T_node;
      maxi(qnode(d,bx,by))=max(max(Quad));

      % fin du bloc
30      if d < D, % prepare for finer scales
        quad = DownQuad(Quad,qmf,by,bx);
        quadI = DownQuad(QuadI,qmf,by,bx);
        coef(lox:hix,loy:hiy) = quad;
35        coefI(lox:hix,loy:hiy) = quadI;
        end
      end
    end
    boxlen = boxlen/2;
40    boxcnt = boxcnt*2;
  end

function out = DiscrDenoise2Radon(basis,img,T,qmf,type)
% DiscrDenoise2 -- Denoising of inverse filtered image
45 %           in best discriminant basis
% Usage
% out = DiscrDenoise2(basis,img,T,qmf,D, maxi)
%
% See Also
50 % WPAAnalysis, DisBasis, Discr
%
%       [n,J] = quadlength(img);
%       coef = img;
%
55 % initialize tree traversal stack
%
%       stack = zeros(3,4*(J+1)+1);

```

```

    k = 1;
    stack(:,k) = [0 0 0]'; % d, bx, by
%
    while(k > 0),
5
        % pop stack
        d = stack(1,k);
        bx = stack(2,k);
        by = stack(3,k);
10
        k=k-1;
        [lox hix loy hiy] = quadbounds(d,bx,by,n);
        Quad = coef(lox:hix,loy:hiy);

        if (basis(qnode(d,bx,by)) ~= 0) , % nonterminal node
15
            quad = DownQuad(Quad,qmf,bx,by);
            coef(lox:hix,loy:hiy) = quad;

            % push stack
            k = k+1; stack(:,k) = [(d+1) (2*bx) (2*by) ]';
20
            k = k+1; stack(:,k) = [(d+1) (2*bx+1) (2*by) ]';
            k = k+1; stack(:,k) = [(d+1) (2*bx) (2*by+1) ]';
            k = k+1; stack(:,k) = [(d+1) (2*bx+1) (2*by+1) ]';

        else
            coef(lox:hix,loy:hiy)=Quad;
25
            thresh=T(qnode(d,bx,by));
            if strcmp(type,'A'),
                coef(lox:hix,loy:hiy) = AffineThresh(Quad,
thresh);
            end
            if strcmp(type,'S'),
30
                coef(lox:hix,loy:hiy) = SoftThresh(Quad, thresh);
            end
            if strcmp(type,'H'),
                coef(lox:hix,loy:hiy) = HardThresh(Quad, thresh);
35
            end
        end
    end

    out = IPT2_WP(basis,coef,qmf);
40


---


function d = DownDyadHi(x,qmf)
% DownDyadHi -- Hi-Pass Downsampling operator (periodized)
% Usage
%   d = DownDyadHi(x,f)
45
% Inputs
%   x    1-d signal at fine scale
%   f    filter
% Outputs
%   y    1-d signal at coarse scale
50
%
% See Also
%   DownDyadLo, UpDyadHi, UpDyadLo, FWT_PO, iconv
%
    d = iconv( MirrorFilt(qmf),lshift(x));
55
    n = length(d);
    d = d(1:2:(n-1));

```

```

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%

function d = DownDyadLo(x,qmf)
15 % DownDyadLo -- Lo-Pass Downsampling operator (periodized)
% Usage
%   d = DownDyadLo(x,f)
% Inputs
%   x    1-d signal at fine scale
20 %   f    filter
% Outputs
%   y    1-d signal at coarse scale
%
% See Also
25 %   DownDyadHi, UpDyadHi, UpDyadLo, FWT_PO, aconv
%
%   d = aconv(qmf,x);
%   n = length(d);
%   d = d(1:2:(n-1));
30
%
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%

function q = DownQuad(Quad,qmf,xbit,ybit)
45 % DownQuad -- Split 2-d image into 4 subbands
% Usage
%   q = DownQuad(Quad,qmf,xbit,ybit)
% Inputs
%   Quad  Quadlet to be split into four subbands
50 %   qmf  orthogonal quadrature mirror filter
%   xbit  x-position of quadlet in 2-d freq plane
%   ybit  y-position of quadlet in 2-d freq plane
% Outputs
%   q     quadlet after splitting
55 %
% Description
%   A 2-d signal is split into four subbands: (Lo_x,Lo_y),

```

```

%      (Lo_x,Hi_y), (Hi_x,Lo_y), (Hi_x,Hi_y).
%
%      This routine is called by other, higher-level WaveLab functions
%      and may not be useful for many users.
5
%      See Also
%      FPT2_WP, UpQuad
%

10      [nr,nc] = size(Quad);
      q      = zeros(nr,nc);
      ybit = rem(ybit,2);
      xbit = rem(xbit,2);
%
15      bot = 1:(nc/2);
      top = bot + (nc/2);
%
      for i=1:nr,
          lpchan = DownDyadLo(Quad(i,:),qmf);
          hpchan = DownDyadHi(Quad(i,:),qmf);
20      %      lpchan = ddc(Quad(i,:),qmf);
          %      hpchan = ddd(Quad(i,:),qmf);
          if xbit,
              q(i,top) = lpchan;
              q(i,bot) = hpchan;
25      else
                  q(i,top) = hpchan;
                  q(i,bot) = lpchan;
          end
30      end
%
      bot = 1:(nr/2);
      top = bot + (nr/2);
%
35      for j=1:nc,
          lpchan = DownDyadLo(q(:,j)',qmf)';
          hpchan = DownDyadHi(q(:,j)',qmf)';
          %      lpchan = ddc(q(:,j)',qmf)';
          %      hpchan = ddd(q(:,j)',qmf)';
40      if ybit,
                  q(top,j) = lpchan;
                  q(bot,j) = hpchan;
          else
              q(top,j) = hpchan;
              q(bot,j) = lpchan;
45      end
          end
      end
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55

```

```

function
recim=filtback(sinogram,filtertype,X,deltarho,deltax,rhowindow,interp
ol)
% filtback
5 %
% A routine for computing the inverse Radon transform from a
(rho,theta)
% sinogram.
%
10 % Peter Toft
% Department of Mathematical Modelling,
% Technical University of Denmark
% 1997

15 global INTERPOL FILTERTYPE DEBUGLEVEL

if length(DEBUGLEVEL)==0
    DEBUGLEVEL=0;
end
20
if nargin==0
    sinogram=zeros(101,100);
    sinogram((1+size(sinogram,1))/2,:)=ones(1,size(sinogram,2));
    here=0
25 if DEBUGLEVEL>0,
    figure;
    imagesc(sinogram);
    colorbar;
    colormap(gray(64));
30 title('Demo sinogram');
    drawnow
    end
end

35 [NoRho,NoTheta]=size(sinogram);

if nargin<2
    if length(FILTERTYPE)>0,
        filtertype=FILTERTYPE;
40 if DEBUGLEVEL>0
        disp('Using global setting of the variable filtertype');
    end
    else
        filtertype='ramp';
45 if DEBUGLEVEL>0
        fprintf('Using default setting of the variable filtertype
%s\n',filtertype);
    end
    end
50 end

if nargin<3
    X=NoRho;
    if DEBUGLEVEL>0
55 fprintf('Using default setting of the variable X = %i\n',X);
    end
end

```

```

    if nargin<4
        deltarho=1;
        if DEBUGLEVEL>0
5           fprintf('Using default setting of the variable deltarho =
%f\n',deltarho);
        end
    end

10    if nargin<5
        deltax=deltarho;
        if DEBUGLEVEL>0
            fprintf('Using default setting of the variable deltax =
%f\n',deltax);
15        end
    end

    if nargin<6
        rhowindow=0;
20        if DEBUGLEVEL>0
            fprintf('Using default setting of the variable rhowindow =
%i\n',rhowindow);
        end
    end

25    if nargin<7
        if length(INTERPOL)>0,
            interpol=INTERPOL;
            if DEBUGLEVEL>0
30                disp('Using global setting of the variable interpol');
            end
        else
            interpol=1;
            if DEBUGLEVEL>0
35                fprintf('Using default setting of the variable interpol =
%i\n',interpol);
            end
        end
    end

40    % Hann windowing to avoid edge effects

    if rhowindow==1,
        HannWindow=0.5*(1-cos(2*pi/(NoRho-1)*(0:NoRho-1)))';
45    sinogram=sinogram.*(HannWindow*ones(1,NoTheta));
    end

    % Filtering

50    %Valid for nearest neighbour and linear interpolation only

    maxrho=sqrt(2.0)*(X-1)/2*deltax;
    NoRhoExt=max(1+2*ceil(maxrho/deltarho+1),NoRho);

55    halfadd1NoRho=round(0.5*(NoRhoExt-NoRho));

    sinogramext=zeros(NoRhoExt,NoTheta);

```

```

sinogramext(1+halfadd1NoRho:NoRho+halfadd1NoRho,:)=sinogram;

NoRhoExth=(NoRhoExt-1)/2;
if strcmp(lower(filtertype), 'ramp')==1,
5   disp('Using Ramp filter')
   filterf=[0:NoRhoExth]*0.5/NoRhoExth/deltarho;
elseif strcmp(lower(filtertype), 'shepplogan')==1,
   disp('Using Shepp Logan filter');
   filterf=sin(pi/2*[0:NoRhoExth]/NoRhoExth)/pi/deltarho;
10  elseif strcmp(lower(filtertype), 'sine')==1,
   disp('Using sin filter');
   filterf=sin(pi*[0:NoRhoExth]/NoRhoExth)/pi/deltarho*0.5;
   else
   disp('Unknown method.')
15  end

filterfunc=[filterf filterf(NoRhoExth:-1:1)'];

%Filtering
20  fsinogramext=real(ifft(fft(sinogramext).*(filterfunc*ones(1,NoTheta))
));

%if DEBUGLEVEL>1,
% figure
25 % imagesc(fsinogramext)
% colormap gray
% colorbar
% drawnow;
%end

30 % Backprojection
recim=zeros(X,X);

relxar=((0:X-1)-(X-1)/2)*deltax/deltarho;
35 thetaindices=(0:NoTheta-1);
thetaar=thetaindices/NoTheta*2*pi;
cosar=cos(thetaar);
sinar=sin(thetaar);
xcosar=cosar'*relxar;
40 ysinar=sinar'*relxar+(NoRhoExt-1)/2;
thetaimat=thetaindices'*ones(1,X);

%xcosar(t,m)=x(m)*cos(theta(t))
%ycosar(t,m)=y(m)*sin(theta(t))+offset
45 if interpol==0,
   for xi=1:X,
    % fprintf('%4i (%i)\r',xi,X);
    rhomat=ysinar+xcosar(:,xi)*ones(1,X);
50    rhoimat=round(rhomat);
    indmat=rhoimat+1+NoRhoExt*thetaimat;
    for yi=1:X,
     recim(yi,xi)=sum(fsinogramext(indmat(:,yi)));
    end
55   end
   else
   for xi=1:X,

```



```

%   fprintf('%4i (%i)\r',xi,X);
    rhomat=ysinar+xcosar(:,xi)*ones(1,X);
    rhoimat=floor(rhomat);
    drho=rhomat-rhoimat;
5   indmat=rhoimat+1+NoRhoExt*thetaimat;
    for yi=1:X,
        recim(yi,xi)=sum(drho(:,yi).*fsinogramext(1+indmat(:,yi))+(1-
drho(:,yi)).*fsinogramext(indmat(:,yi)));
        end
10   end
    end

    recim=recim*pi/NoTheta;

15   recim(:, :)=recim(X:-1:1, :);

    fprintf('Done with filtered backprojection\n');

    if DEBUGLEVEL>1,
20   figure;
        imagesc(recim);
        colorbar;
        colormap(gray(64));
        title('Reconstructed image');
25   drawnow;
    end



---


function x = HardThresh(y,t)
% HardThresh -- Apply Hard Threshold
30 % Usage
%   x = HardThresh(y,t)
% Inputs
%   y      Noisy Data
%   t      Threshold
35 % Outputs
%   x      y 1_{|y|>t}
%
%       x  = y .* (abs(y) > t);

40 %
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%



---


function y = iconv(f,x)
55 % iconv -- Convolution Tool for Two-Scale Transform
% Usage
%   y = iconv(f,x)

```

```

% Inputs
%   f   filter
%   x   1-d signal
% Outputs
5 %   y   filtered result
%
% Description
%   Filtering by periodic convolution of x with f
%
10 % See Also
%   aconv, UpDyadHi, UpDyadLo, DownDyadHi, DownDyadLo
%
    n = length(x);
    p = length(f);
15    if p <= n,
        xpadding = [x((n+1-p):n) x];
    else
        z = zeros(1,p);
        for i=1:p,
20            imod = 1 + rem(p*n - p + i - 1, n);
            z(i) = x(imod);
        end
        xpadding = [z x];
    end
25    ypadding = filter(f,1,xpadding);
    y = ypadding((p+1):(n+p));

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%

40 function img = IPT2_WP(basis,coef,qmf)
% IPT2_WP -- Synthesize image from 2-d wavelet packet coefficients
% Usage
%   img = IPT2_WP(btrees,coef,qmf)
45 % Inputs
%   btrees   Quad Tree indicating wavelet packet to use
%   coef     2-d wavelet packet coeffs in given basis
%   qmf      quadrature mirror filter
% Outputs
50 %   img     2-d image whose 2-d wavelet packet coeffs in
%           basis are coef
% Description
%   Perform the inverse operation of FPT2_WP.
%
55     [n,J] = quadlength(coef);
    img = coef;

```

```

% initialize tree traversal stack
stack = zeros(4,4*(J+1)+1);
k = 1;
5   stack(:,k) = [0 0 0 0]'; % d, bx, by, unmarked
%
while(k > 0),
    % pop stack
10   d = stack(1,k);
    bx = stack(2,k); by = stack(3,k);
    marked = stack(4,k); k=k-1;
    % fprintf('d bx by'); disp([d bx by])

15   if(basis(qnode(d,bx,by)) ~= 0) , % nonterminal node
        if(marked == 0),
            % first visit, because unmarked
20           % pushdown (marked) self
            % pushdown unmarked children

            k = k+1; stack(:,k) = [d bx by 1]';
            k = k+1; stack(:,k) = [(d+1) (2*bx) (2*by)
25   0]';
            k = k+1; stack(:,k) = [(d+1) (2*bx+1) (2*by)
            0]';
            k = k+1; stack(:,k) = [(d+1) (2*bx)
30   (2*by+1) 0]';
            k = k+1; stack(:,k) = [(d+1) (2*bx+1)
            (2*by+1) 0]';
        else

            % second (&last) visit, because marked
35           % reconstruct -- apply UpQuad operator

            [lox hix loy hiy] = quadbounds(d,bx,by,n);
            %fprintf(' [lox hix loy hiy] '); disp([lox hix
40   loy hiy])

            quad = img(lox:hix,loy:hiy);
            Quad = UpQuad(quad,qmf,by,bx);
            img(lox:hix,loy:hiy) = Quad;

            end
45         end
    end
end

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```

```

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%


---


function f = MakeONFilter(Type,Par)
5 % MakeONFilter -- Generate Orthonormal QMF Filter for Wavelet
  Transform
  % Usage
  %   qmf = MakeONFilter(Type,Par)
  % Inputs
10 %   Type      string, 'Haar', 'Beylkin', 'Coiflet', 'Daubechies',
    %           'Symmlet', 'Vaidyanathan','Battle'
  %   Par       integer, it is a parameter related to the support and
    vanishing
    %           moments of the wavelets, explained below for each
15 wavelet.
  %
  % Outputs
  %   qmf       quadrature mirror filter
  %
20 % Description
  %   The Haar filter (which could be considered a Daubechies-2) was
    the
    %   first wavelet, though not called as such, and is discontinuous.
  %
25 %   The Beylkin filter places roots for the frequency response
    function
    %   close to the Nyquist frequency on the real axis.
  %
  %   The Coiflet filters are designed to give both the mother and
30 father
  %   wavelets 2*Par vanishing moments; here Par may be one of 1,2,3,4
    or 5.
  %
  %   The Daubechies filters are minimal phase filters that generate
35 wavelets
  %   which have a minimal support for a given number of vanishing
    moments.
  %   They are indexed by their length, Par, which may be one of
  %   4,6,8,10,12,14,16,18 or 20. The number of vanishing moments is
40 par/2.
  %
  %   Symmlets are also wavelets within a minimum size support for a
    given
    %   number of vanishing moments, but they are as symmetrical as
45 possible,
  %   as opposed to the Daubechies filters which are highly
    asymmetrical.
  %   They are indexed by Par, which specifies the number of vanishing
  %   moments and is equal to half the size of the support. It ranges
50 from 4 to 10.
  %
  %   The Vaidyanathan filter gives an exact reconstruction, but does
    not
    %   satisfy any moment condition. The filter has been optimized for
55 %   speech coding.
  %

```

```

% The Battle-Lemarie filter generate spline orthogonal wavelet
basis.
% The parameter Par gives the degree of the spline. The number of
% vanishing moments is Par+1.
5 %
% See Also
% FWT_PO, IWT_PO, FWT2_PO, IWT2_PO, WPAAnalysis
%
% References
10 % The books by Daubechies and Wickerhauser.
%

if strcmp(Type,'Haar'),
    f = [1 1] ./ sqrt(2);
15 end

if strcmp(Type,'Beylkin'),
    f = [ .099305765374      .424215360813      .699825214057      ...
          .449718251149      -.110927598348      -.264497231446
20      ...
          .026900308804      .155538731877      -.017520746267
          ...
          -.088543630623      .019679866044      .042916387274
          ...
25      -.017460408696      -.014365807969      .010040411845
          ...
          .001484234782      -.002736031626      .000640485329
    ];
end
30

if strcmp(Type,'Coiflet'),
    if Par==1,
        f = [ .038580777748      -.126969125396      -.077161555496
35      ...
          .607491641386      .745687558934
          .226584265197      ];
        end
        if Par==2,
            f = [ .016387336463      -.041464936782      -.067372554722
40      ...
          .386110066823      .812723635450
          .417005184424      ...
          -.076488599078      -.059434418646
          .023680171947      ...
45      .005611434819      -.001823208871      -
          .000720549445      ];
        end
        if Par==3,
            f = [ -.003793512864      .007782596426      .023452696142
50      ...
          -.065771911281      -.061123390003
          .405176902410      ...
          .793777222626      .428483476378      -
          .071799821619      ...
55      -.082301927106      .034555027573
          .015880544864      ...

```

```

        .001117518771      -.009007976137      -.002574517688
        ...
        .000466216960      -.000070983303      -
5      .000034599773      ];
      end
      if Par==4,
        f = [ .000892313668      -.001629492013      -.007346166328
        ...
        .016068943964      .026682300156      -
10     .081266699680      ...
        .782238930920      -.056077313316      .415308407030
        ...
        .434386056491      -.066627474263      -
        .096220442034      ...
15     .015211731527      ...
        .039334427123      .025082261845      -
        .005658286686      .003751436157
        .001266561929      ...
        -.000589020757      -.000259974552
20     .000062339034      ...
        .000031229876      -.000003259680      -
        .000001784985      ];
      end
      if Par==5,
25     f = [ -.000212080863      .000358589677      .002178236305
        ...
        -.004159358782      -.010131117538
        .023408156762      ...
        .028168029062      -.091920010549      -
30     .052043163216      ...
        .421566206729      .774289603740
        .437991626228      ...
        -.062035963906      -.105574208706
        .041289208741      ...
35     .032683574283      -.019761779012      -
        .009164231153      ...
        .006764185419      .002433373209      -
        .001662863769      ...
        -.000638131296      .000302259520
40     .000140541149      ...
        -.000041340484      -.000021315014
        .000003734597      ...
        .000002063806      -.000000167408      -
        .000000095158      ];
45     end
      end

      if strcmp(Type, 'Daubechies'),
        if Par==4,
50         f = [ .482962913145      .836516303738      ...
        .224143868042      -.129409522551      ];
        end
        if Par==6,
55         f = [ .332670552950      .806891509311      ...
        .459877502118      -.135011020010      ...
        -.085441273882      .035226291882      ];
        end

```

```

        if Par==8,
            f = [ .230377813309      .714846570553      ...
                  .630880767930      -.027983769417      ...
                  -.187034811719      .030841381836      ...
                  .032883011667      -.010597401785      ];
5
        end
        if Par==10,
            f = [ .160102397974      .603829269797      .724308528438
                  ...
                  .138428145901      -.242294887066      -
                  .032244869585      ...
                  .077571493840      -.006241490213      -
                  .012580751999      ...
                  .003335725285
15
                  ];
        end
        if Par==12,
            f = [ .111540743350      .494623890398      .751133908021
                  ...
                  .315250351709      -.226264693965      -
                  .129766867567      ...
                  .097501605587      .027522865530      -
                  .031582039317      ...
                  .000553842201      .004777257511      -
25
                  ];
        end
        if Par==14,
            f = [ .077852054085      .396539319482      .729132090846
                  ...
                  .469782287405      -.143906003929      -
                  .224036184994      ...
                  .071309219267      .080612609151      -
                  .038029936935      ...
                  -.016574541631      .012550998556
35
                  .000429577973      ...
                  -.001801640704      .000353713800
                  ];
        end
        if Par==16,
            f = [ .054415842243      .312871590914      .675630736297
                  ...
                  .585354683654      -.015829105256      -
                  .284015542962      ...
                  .000472484574      .128747426620      -
45
                  .017369301002      ...
                  -.044088253931      .013981027917
                  .008746094047      ...
                  -.004870352993      -.000391740373
                  .000675449406      ...
50
                  -.000117476784
                  ];
        end
        if Par==18,
            f = [ .038077947364      .243834674613      .604823123690
                  ...
                  .657288078051      .133197385825      -
55
                  .293273783279      ...

```

```

    .030725681479    -.096840783223    .148540749338
    .022361662124    ...
    .001847646883    -.067632829061    .000250947115
    .000039347320    -.004723204758    -.004281503682
    end              ...
    if Par==20,      .000230385764    -.000251963189
        f = [ .026670057901    .188176800078    .527201188932
        ...
        .688459039454    .281172343661    -
        .249846424327    ...
        .093057364604    -.195946274377    .127369340336
        .033212674059    -.071394147166    -.029457536822
        .001395351747    .003606553567    -.010733175483
        .000116466855    .001992405295    -.000685856695    -
        .000093588670    -.000013264203
        ];
    end
end

if strcmp(Type,'Symmlet'),
    if Par==4,
        f = [ -.107148901418    -.041910965125    .703739068656
        ...
        1.136658243408    .421234534204    -
        .140317624179    ...
        -.017824701442    .045570345896
        ];
    end
    if Par==5,
        f = [ .038654795955    .041746864422    -.055344186117
        ...
        .281990696854    1.023052966894
        .896581648380    .023478923136    -.247951362613    -
        .029842499869    .027632152958
        ];
    end
    if Par==6,
        f = [ .021784700327    .004936612372    -.166863215412
        ...
        -.068323121587    .694457972958
        1.113892783926    .477904371333    -.102724969862    -
        .029783751299    .063250562660    .002499922093    -
        ];
    end
    if Par==7,

```



```

      f = [ .003792658534      -.001481225915      -.017870431651
      ...
      .043155452582      .096014767936      -
5  .070078291222      ...
      1.085782709814      ...
      .024665659489      .758162601964
      .408183939725      -.198056706807      -
      .152463871896      ...
      .005671342686      .014521394762
10      ];
      end
      if Par==8,
      f = [ .002672793393      -.000428394300      -.021145686528
      ...
      .005386388754      .069490465911      -
15  .038493521263      ...
      -.073462508761      .515398670374
      1.099106630537      ...
      .680745347190      -.086653615406      -
20  .202648655286      ...
      .010758611751      .044823623042      -
      .000766690896      ...
      -.004783458512
      ];
25  end
      if Par==9,
      f = [ .001512487309      -.000669141509      -.014515578553
      ...
      .012528896242      .087791251554      -
30  .025786445930      ...
      -.270893783503      .049882830959
      .873048407349      ...
      1.015259790832      .337658923602      -
      .077172161097      ...
      .000825140929      .042744433602      -
35  .016303351226      ...
      -.018769396836      .000876502539
      .001981193736      ];
      end
40  if Par==10,
      f = [ .001089170447      .000135245020      -.012220642630
      ...
      -.002072363923      .064950924579
      .016418869426      ...
      -.225558972234      -.100240215031
45  .667071338154      ...
      1.088251530500      .542813011213      -
      .050256540092      ...
      -.045240772218      .070703567550
50  .008152816799      ...
      -.028786231926      -.001137535314
      .006495728375      ...
      .000080661204      -.000649589896
      ];
55  end
end

```

```

    if strcmp(Type, 'Vaidyanathan'),
        f = [ -.000062906118      .000343631905      -.000453956620      ...
              -.000944897136      .002843834547      .000708137504
5          ...
              -.008839103409      .003153847056      .019687215010
              ...
              -.014853448005      -.035470398607      .038742619293
              ...
              .055892523691      -.077709750902      -.083928884366
10          ...
              .131971661417      .135084227129      -.194450471766
              ...
              -.263494802488      .201612161775      .635601059872
              ...
15          ...
              .572797793211      .250184129505      .045799334111
              ];
    end

    if strcmp(Type, 'Battle'),
20        if Par == 1,
            g = [0.578163      0.280931      -0.0488618      -0.0367309 ...
                  0.012003      0.00706442 -0.00274588 -0.00155701 ...
                  0.000652922 0.000361781 -0.000158601 -0.0000867523
25          ];
        end

        if Par == 3,
            g = [0.541736      0.30683      -0.035498      -0.0778079 ...
                  0.0226846      0.0297468      -0.0121455 -0.0127154 ...
                  0.00614143 0.00579932      -0.00307863 -0.00274529 ...
                  0.00154624 0.00133086 -0.000780468 -0.00065562 ...
                  0.000395946 0.000326749 -0.000201818 -0.000164264 ...
30          ...
                  0.000103307
35          ];
        end

        if Par == 5,
40          g = [0.528374      0.312869      -0.0261771      -0.0914068 ...
                  0.0208414      0.0433544 -0.0148537 -0.0229951 ...
                  0.00990635 0.0128754      -0.00639886 -0.00746848 ...
                  0.00407882 0.00444002 -0.00258816      -0.00268646 ...
                  0.00164132 0.00164659 -0.00104207 -0.00101912 ...
                  0.000662836 0.000635563 -0.000422485 -0.000398759 ...
45          ...
                  0.000269842 0.000251419 -0.000172685 -0.000159168 ...
                  0.000110709 0.000101113
                    ];
        end

        l = length(g);
50        f = zeros(1, 2*l-1);
        f(1:2*l-1) = g;
        f(1:l-1) = reverse(g(2:l));

    end

55    f = f ./ norm(f);

    %

```

```

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%

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10 %

function [maxi,tree,T] = NonPrior2dStatTree(img,D,qmf,I,mult_sigma)

15 [n,J] = quadlength(img);
boxlen = n;
boxcnt = 1;
coef = img;
coefI = I;

20 for d = 0:D,
    for bx=0:(boxcnt-1),
        for by=0:(boxcnt-1),

25         [lox,hix,loy,hiy] = quadbounds(d,bx,by,n);
        Quad = coef(lox:hix,loy:hiy);
        QuadI = coefI(lox:hix,loy:hiy);

        [s1,s2]=size(Quad);

30         sigma=sqrt(1/(s1*s2)*sum(sum(QuadI.*QuadI)));

        % [y,estim] = NormNoise(Quad,qmf);
35         % sigma=1/estim

        T_node=mult_sigma*sigma;

        r1= abs(Quad) < T_node;
        r2=1-r1;
40         Quad=sign(Quad).*(abs(Quad)-sigma);
        p1=Quad.^2;
        pt1=p1.*r1;
        p2=(T_node^2+sigma^2)*ones(size(Quad));
45         pt2=p2.*r2;
        tree(qnode(d,bx,by)) = sum(sum(pt1))+sum(sum(pt2));
        T(qnode(d,bx,by)) = T_node;
        maxi(qnode(d,bx,by))=max(max(Quad));

50         % fin du bloc

        if d < D, % prepare for finer scales
            quad = DownQuad(Quad,qmf,by,bx);
55            quadI = DownQuad(QuadI,qmf,by,bx);
            coef(lox:hix,loy:hiy) = quad;
            coefI(lox:hix,loy:hiy) = quadI;

```

```

        end
    end
    end
    boxlen = boxlen/2;
5    boxcnt = boxcnt*2;
end

function [y,coef] = NormNoise(x,qmf)
% NormNoise -- Estimates noise level, Normalize signal to noise level
10 1
% Usage
% [y,coef] = NormNoise(x,qmf)
% Inputs
% x      1-d signal
15 % qmf   quadrature mirror filter
% Outputs
% y      1-d signal, scaled so wavelet coefficients
%        at finest level have median absolute deviation 1.
% coef   estimation of 1/sigma
20 %
% Description
% This is required pre-processing to use any of the DeNoising
% tools on naturally-occurring data.
%
25 % See Also
% WaveShrink, CPDeNoise, WPDeNoise
%
    u = DownDyadHi(x,qmf);
    s = median(abs(u));
30 if s ~= 0
        y = .6745 .* x ./s;
        coef = .6745 /s;
    else
        y = x;
35         coef = 1;
    end
end

%
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40 Johnstone
%
% Modified by Maureen Clerc and Jerome Kalifa, 1997
% clerc@cmapx.polytechnique.fr, kalifa@cmapx.polytechnique.fr
%
45 %
%
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%

55 function ix = qnode(d,bx,by)
% qnode -- Quad tree indexing
% Usage

```

```

%   ix = qnode(d,bx,by)
%   Inputs
%       d       depth in splitting
%       bx,by   box coordinates at that depth
5  %   Outputs
%       ix      index of that node in tree
%
%   Description
%       ix = 4^(d) + by + bx*2^(d)
10 %
%
%       ix = 4^(d) + by + bx*2^(d);
%
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%
20

```

```

function [lox,hix,loy,hiy] = quadbounds(d,bx,by,n)
% quadbounds -- x,y bounds of quadlet
% Usage
25 %   [lox,hix,loy,hiy] = quadbounds(d,bx,by,n)
%   Inputs
%       d       depth in splitting
%       bx,by   box coordinates at that depth.
%       n       extent of image
30 %   Outputs
%       lox     lower x-index of quadlet
%       loy     lower y-index of quadlet
%       hix     upper x-index of quadlet
%       hiy     upper y-index of quadlet
35 %
%   Description
%       This routine is called by other, higher-level Wavelab functions
%       and is not intended to be useful for most users.
%
40 %       boxsize = n/(2^d);
%       lox = bx*boxsize+1;
%       loy = by*boxsize+1;
%       hix = (bx+1)*boxsize;
%       hiy = (by+1)*boxsize;
45 %
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```

```

55 function [n,J] = quadlength(x)
% quadlength -- Find length and dyadic length of square matrix
% Usage

```

```

% [n,J] = quadlength(x)
% Inputs
% x 2-d image; size(n,n), n = 2^J (hopefully)
% Outputs
5 % n length(x)
% J least power of two greater than n
%
% Side Effects
% A warning message is issue if n is not a power of 2,
10 % or if x is not a square matrix.
%
% s = size(x);
% n = s(1);
% if s(2) ~= s(1),
15 % disp('Warning in quadlength: nr != nc')
% end
% k = 1 ; J = 0; while k < n , k=2*k; J = 1+J ; end ;
% if k ~= n ,
% disp('Warning in quadlength: n != 2^J')
20 % end
%
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---


35 function x = SoftThresh(y,t)
% SoftThresh -- Apply Soft Threshold
% Usage
% x = SoftThresh(y,t)
% Inputs
40 % y Noisy Data
% t Threshold
% Outputs
% x sign(y) (|y|-t)_+
%
45 % res = (abs(y) - t);
% res = (res + abs(res))/2;
% x = sign(y).*res;
%
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```

```

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5
function
Inv_Recons=SPECTMacrTomoFiltback(num,preDenoise,postDenoise,mult_pre,
mult_post,fileproj,type1,type2)
%
10 % Macro for tomographic reconstruction methods using SPECT Interfile
data
% With an adaptive selection of the wavelet packet basis
%

15 dime=128;

sino = Decodefile(fileproj, num);
sino(:, :)=Big2Little(sino(:, :));
Theta=0:2.82:360; % Projection angles

20 % Estimation of the Noise level

qmf = MakeONFilter('Symmlet',4);

25 [y,coef] = NormNoise(sino,qmf);
sigma=1/coef

Inv_Degr=filtback(sino);

30 if postDenoise==1
% Uncomment if you want to use a Phantom Image as prior model for
the
% image

35 % Phant=raw2mat('phantom128.gray',128,128);
B=(randn(size(sino)))*sigma; % Noise generation

Inv_B= filtback(B);

40 D=3;
% If one uses a Phantom to choose the basis

% [maxi,tree,T] = Dis2dStatTree(Phant,D,qmf,Inv_B,mult_post);

45 % If one uses the degraded data to choose the basis

[maxi,tree,T] =
NonPrior2dStatTree(Inv_Degr,D,qmf,Inv_B,mult_post);

50 btree = Best2dBasis(tree,D);
% ax = axis; hold;
% Plot2dPartition(btree,'y',ax,D);
Rest_best=zeros(size(Inv_Degr));
lim=2;

55 for i=1:lim,
for j=1:lim,

```

```

        [Inv_Degrtrans] = cyclespin2(Inv_Degr,i,j);
        [Rest] =DiscrDenoise2Radon(btree,Inv_Degrtrans,0*T,qmf,'H');
        [Rest] = cyclespin2(Rest,dime-i,dime-j);
        Rest_best = Rest_best+Rest;
5      end
      end

      Rest_best=Rest_best/(lim*lim);
      Inv_Recons=Rest_best;
10   end

%
15  % (c) Jérôme Kalifa, 2000
    % kalifa@columbia.edu
    %



---


function Rest_best=SPECTTomo(num,mult,fileproj,type)
20
% size of the images

dime=128;

25  % Read Interfile projections for the slice #num

sino = Decodefile(fileproj, num);

% Big Endian --> Little Endian
30  sino(:,:)=Big2Little(sino(:,:));

% Projection angles

35  Theta=0:2.82:360;

% Filter to be used by the wavelet(packet) transform

qmf = MakeONFilter('Symmlet',4);
40
% D= 2 or 3 is fine (3 slightly better, but slower);
D=2;

% Simulation of the backprojected noise, 1st alternative
45
[y,coef] = NormNoise(sino,qmf);
sigma=1/coef;
B=(randn(size(sino)))*sigma;

50  % 2nd alternative, using numerical measurements

%out=ThreshWave2(sino,'H');
%B=sino-out;

55  % Generation of the backprojected noise, and measurement of the
    amplitude of

```



```

% its coefficients in the WP tree. NB: If the noise B has been
generated
% with 1st alternative, it is possible to avoid this step by storing
a array
5 % A of noise amplification values for the WP coefficients, and
computing
% AmpNoise=sigma.*A .

Inv_B= filtbac(B);
10 AmpNoise= TomoStatTree(D,qmf,Inv_B);

% Wavelet packet basis we want to use.

if D==2;
15     btree = zeros(1,31);
        btree(1)=1;
        btree(5:6)=[1 1];
elseif D==3;
        btree = zeros(1,127);
20     btree(1)=1;
        btree(5:7)=[1 1 1];
        btree(26:27)=[1 1];
        btree(30:31)=[1 1];
end
25 % Reconstruction by BackProjection, just ramp filtering

Inv_Degr=filtbac(sino);

30 % Initialisation of the final image

Rest_best=zeros(dime,dime);

% Translation-invariance. lim=4 slightly better than lim=2, but
35 slower.
lim=2;

% Denoising in the wavelet packet tree.

40 for i=1:lim,
    for j=1:lim,
        [Inv_Degrtrans] = cyclespin2(Inv_Degr,i,j);
        [Rest] = TomoDenoise(btree,Inv_Degrtrans,AmpNoise,qmf,type,mult);
        [Rest] = cyclespin2(Rest,dime-i,dime-j);
45     Rest_best = Rest_best+Rest;
    end
end

Rest_best=Rest_best/(lim*lim);
50 Rest_Int=Rest_best;

% Denoising in the wavelet tree

Rest_best=zeros(size(Rest_Int));
55 btree=zeros(size(btree));
    btree(1)=1;
    btree(4)=1;

```

```

lim=2;

for i=1:lim,
    for j=1:lim,
5      [Rest_Inttrans] = cyclespin2(Rest_Int,i,j);
      [Rest] =TomoDenoise(btrees,Rest_Inttrans,AmpNoise,qmf,'H',mult);
      [Rest] = cyclespin2(Rest,dime-i,dime-j);
      Rest_best = Rest_best+Rest;
    end
10  end

% Regularized reconstructed image

Rest_best=Rest_best/(lim*lim);
15

%
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% kalifa@columbia.edu
%

20
function out=ThreshWave2Aff(Noisy,type,TI,sigma,mult,L,qmf)
% ThreshWave2 -- Denoising of 2-d image with wavelet thresholding.
% Usage
% out=ThreshWave2(Noisy,type,TI,sigma,mult,L,qmf)
25 % Inputs
% Noisy 2-d Noisy image, size(Noisy)= 2^J*2^J.
% type 'S' for soft thresholding, 'H' for hard
thresholding.
% Optional, Default=hard thresholding.
30 % TI Enter 1 if you want translation-invariant
denoising,
% 0 if you don't.
% Optional, Default=non-invariant.
% sigma Standard deviation of additive Gaussian White
35 Noise.
% Enter 0 if you want sigma to be estimated by median
filtering.
% Optional, Default=estimated by median filtering.
% mult Multiplier of sigma to obtain the value of the
40 threshold.
% Optional, Default = sqrt(2*log(n)), where n is the
number of pixels/
% L Low-Frequency cutoff for shrinkage (e.g. L=4)
% Should have L << J!
45 % Optional, Default = 3.
% qmf Quadrature Mirror Filter for Wavelet Transform
% Optional, Default = Symmlet 4.
% Outputs
% out Estimate, obtained by applying thresholding on
50 % wavelet coefficients.
%

n=length(Noisy);
if nargin < 7,
55 qmf = MakeONFilter('Symmlet',4);
end
if nargin < 6,

```

```

        L = 3;
    end
    if nargin < 5,
        mult = sqrt(4*log(n));
5    end
    if nargin < 4,
        [y,coef] = NormNoise(Noisy,qmf);
        sigma=1/coef;
    end
10    if nargin < 3,
        TI = 0;
    end
    if nargin < 2,
        type = 'H';
15    end

    if sigma==0,
        [y,coef] = NormNoise(Noisy,qmf);
        sigma=1/coef;
20    end

    thresh= sigma*mult;
    out=zeros(1,n);

25    if TI==1,
        if strcmp(type,'S'),
            out=TIDnoiseSoft2(Noisy,L,qmf,thresh);
        end
30    if strcmp(type,'H'),
        out=TIDnoiseHard2(Noisy,L,qmf,thresh);
        end
        if strcmp(type,'A'),
            out=TIDnoiseAffine2(Noisy,L,qmf,thresh);
35    end
        else
            if strcmp(type,'S'),
                out=ST2(Noisy,L,qmf,thresh);
            end
40    if strcmp(type,'H'),
                out=HT2(Noisy,L,qmf,thresh);
            end
            if strcmp(type,'A'),
                out=AT2(Noisy,L,qmf,thresh);
45    end
        end
    end

    % Written by Maureen Clerc and Jerome Kalifa, 1997
    % clerc@cmapx.polytechnique.fr, kalifa@cmapx.polytechnique.fr
50

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%

5  function out = TomoDenoise(basis,img,AmpNoise,qmf,type,mult)
%
% Usage
% out = TomoDenoise(basis,img,T,qmf,D,type)
10 %

    [n,J] = quadlength(img);
    coef = img;

%
15 % initialize tree traversal stack
%
    stack = zeros(3,4*(J+1)+1);
    k = 1;
    stack(:,k) = [0 0 0]'; % d, bx, by
20 %
    while(k > 0),

        % pop stack
        d = stack(1,k);
25     bx = stack(2,k);
        by = stack(3,k);
        k=k-1;
        [lox hix loy hiy] = quadbounds(d,bx,by,n);
        Quad = coef(lox:hix,loy:hiy);

30     if(basis(qnode(d,bx,by)) ~= 0) , % nonterminal node
        quad = DownQuad(Quad,qmf,bx,by);
        coef(lox:hix,loy:hiy) = quad;

35     % push stack
        k = k+1; stack(:,k) = [(d+1) (2*bx) (2*by) ]';
        k = k+1; stack(:,k) = [(d+1) (2*bx+1) (2*by) ]';
        k = k+1; stack(:,k) = [(d+1) (2*bx) (2*by+1) ]';
        k = k+1; stack(:,k) = [(d+1) (2*bx+1) (2*by+1) ]';

40     else
        coeff_max=max(max(abs(Quad)));
        if (coeff_max > (6.*AmpNoise)),
            thresh=mult.*AmpNoise(qnode(d,bx,by));
            if strcmp(type,'A'),
45                 coef(lox:hix,loy:hiy) = AffineThresh(Quad,
                    thresh);
                end
                if strcmp(type,'S'),
                    coef(lox:hix,loy:hiy) = SoftThresh(Quad,
50                 thresh);
                end
                if strcmp(type,'H'),
                    coef(lox:hix,loy:hiy) = HardThresh(Quad,
55                 thresh);
                end
            else
                % coeff_max

```

```

                                coef(lox:hix,loy:hiy) = zeros(hix-lox+1,hiy-
loy+1);
                                end
                                end
5      end

      out = IPT2_WP(basis,coef,qmf);

```

```

10  function AmpNoise = TomoStatTree(D,qmf,I)

    [n,J] = quadlength(I);
    boxlen = n;
    boxcnt = 1;
    coefI = I;
15  for d = 0:D,
        for bx=0:(boxcnt-1),
            for by=0:(boxcnt-1),

20              [lox,hix,loy,hiy] = quadbounds(d,bx,by,n);
              QuadI = coefI(lox:hix,loy:hiy);

              [s1,s2]=size(QuadI);
              AmpNoise_node= sqrt(1/(s1*s2)*sum(sum(QuadI.*QuadI)));
25              AmpNoise(qnode(d,bx,by)) = AmpNoise_node;

              % prepare for finer scales
              if d < D,
30                  quadI = DownQuad(QuadI,qmf,by,bx);
                  coefI(lox:hix,loy:hiy) = quadI;
                  end
              end
            end
35          boxlen = boxlen/2;
          boxcnt = boxcnt*2;
        end

```

```

40  function Q = UpQuad(quad,qmf,xbit,ybit)
% UpQuad -- Merge four subbands into 2d image
% Usage
%   Q = UpQuad(quad,qmf,xbit,ybit)
% Inputs
45 %   Quad    quadlet to be joined 4->1 channel
%   qmf      orthogonal quadrature mirror filter
%   xbit     x-position of quadlet in 2-d freq plane
%   ybit     y-position of quadlet in 2-d freq plane
% Outputs
50 %   q       quadlet after splitting
%
% Description
%   A 2-d signal split into four channels: (Lo_x,Lo_y),
%   (Lo_x,Hi_y), (Hi_x,Lo_y), (Hi_x,Hi_y) is unsplit
55 %   into original image.
%
%   This routine is called by other, higher-level WaveLab

```

```

%      functions and may not be useful for many users.
%
%      See Also
%      IPT2_WP, DownQuad
5      %
        [nr,nc] = size(quad);
        Q      = zeros(nr,nc);
        ybit = rem(ybit,2);
        xbit = rem(xbit,2);
10      %
        bot = 1:(nr/2);
        top = bot + (nr/2);
        %
        for j=1:nc,
15            if ybit,
                lpchan = quad(top,j)';
                hpchan = quad(bot,j)';
            else
                lpchan = quad(bot,j)';
20                hpchan = quad(top,j)';
            end
            Q(:,j) = UpDyadLo(lpchan,qmf)' + UpDyadHi(hpchan,qmf)';
        end
25      %
        bot = 1:(nc/2);
        top = bot + (nc/2);
        %
        for i=1:nr,
30            if xbit,
                lpchan = Q(i,top);
                hpchan = Q(i,bot);
            else
                lpchan = Q(i,bot);
35                hpchan = Q(i,top);
            end
            Q(i,:) = UpDyadLo(lpchan,qmf) + UpDyadHi(hpchan,qmf);
40      %
        end

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```

APPENDIX B

```

function dwt = FWT_ATrou(x,L);
%
5 % FWT_ATrou -- Fast Dyadic Wavelet Transform (periodized, orthogonal)
% Usage
%   dwt = FWT_ATrou(x,L)
% Inputs
%   x      1-d signal; length(x) = 2^J = n
10 %   L      Coarsest Level of V_0;  L << J
% Outputs
%   dwt     an n times J-L+1 matrix
%           giving the wavelet transform of x at all dyadic scales.
%
15 % Description
%   To reconstruct use IWT_ATrou
%
% See Also
%   IWT_ATrou, MakeATrouFilter
20 %

[lodyadf,dlodyadf,hidyadf,dhidyadf] = MakeATrouFilter('Spline',3);

[n,J] = dyadlength(x) ;
25 D = J-L;
dwt = zeros(n,D+1);
x = ShapeAsRow(x);
dwt(:,1) = x';

30 for d = 1:D,
    s = dwt(:,1)';
    s2 = s;
    for j = 1:2^(d-1)
        s2 = lshift(s2);
35    end
    dwt(:,d+1) = iconv(hidyadf,s)';
    for j = 1:2^d
        p = lshift(dwt(:,d+1)');
40    dwt(:,d+1) = p';
    end
    dwt(:,1) = iconv(lodyadf,s2)';

    f = zeros(1,2*length(lodyadf));
    f(1:2:2*length(lodyadf)-1) = lodyadf;
45    f2 = zeros(1,2*length(hidyadf));
    f2(1:2:2*length(hidyadf)-1) = hidyadf;

    lodyadf = f;
50    hidyadf = f2;
end;

% Written by Maureen Clerc and Jerome Kalifa, 1997
% clerc@cmapx.polytechnique.fr, kalifa@cmapx.polytechnique.fr
55

```

```

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%

function s = IWT_ATrou(dwt,L);
%
10 % IWT_ATrou -- Inverse Dyadic Wavelet Transform
% Usage
%   s = IWT_ATrou(dwt,L)
% Inputs
%   dwt   an n times J-L+1 matrix
15 %   L     Coarsest Level of V_0;  L << J
% Outputs
%   s      original 1-d signal; length(x) = 2^J = n
% Description
%   1. filters are obtained with MakeATrouFilter
20 %   2. usually, length(qmf) < 2^(L+1)
%   3. The transformed signal can be obtained by FWT_ATrou
% See Also
%   FWT_ATrou, MakeATrouFilter
%
25 [n,b] = size(dwt );
J=b+L-1;
if ~(2^J==n)
    fprintf('problem in matrix dimensions');
end
30 s = dwt(:,1)';
D = b-1;
[lodyadf,dlodyadf,hidyadf,dhidyadf] = MakeATrouFilter('Spline',3);

f = zeros(1,2^(D-1)*length(dlodyadf));
35 f(1:2^(D-1):2^(D-1)*length(dlodyadf)+1-2^(D-1)) = dlodyadf;

f2 = zeros(1,2^(D-1)*length(dhidyadf));
f2(1:2^(D-1):2^(D-1)*length(dhidyadf)+1-2^(D-1)) = dhidyadf;

40 for d= D-1:-1:0
    for j = 1:2.*2^(d),2
        s = lshift(s);
    end
    for j = 1:2^(d+1)
45     p = rshift(dwt(:,d+2)');
        dwt(:,d+2) = p';
    end

    for j = 1:3.*2^(d),
50     p=lshift(dwt(:,d+2)');
        dwt(:,d+2)=p';
    end
    s=0.5*(iconv(f,s)+iconv(f2,dwt(:,d+2)'));

55 f = zeros(1,2^(d-1)*length(dlodyadf));
f(1:2^(d-1):2^(d-1)*length(dlodyadf)+1-2^(d-1)) = dlodyadf;

```



```

        f2 = zeros(1,2^(d-1)*length(dhidyadf));
        f2(1:2^(d-1):2^(d-1)*length(dhidyadf)+1-2^(d-1)) = dhidyadf;
    end

5   % Written by Maureen Clerc and Jerome Kalifa, 1997
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    %
15



---


function y = lshift(x)
% lshift -- Circular left shift of 1-d signal
% Usage
20 %   l = lshift(x)
% Inputs
%   x   1-d signal
% Outputs
%   l   1-d signal
25 %   l(i) = x(i+1) except l(n) = x(1)
%

    y = [ x( 2:length(x) ) x(1) ];

30 %
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---


function [lodyadf,dlodyadf,hidyadf,dhidyadf] =
MakeATrouFilter(Type,Par)
45 %
% MakeATrouFilter -- Generate Biorthonormal Quadratic Spline Filter
Pair
%
% Usage
50 %   [lodyadf,dlodyadf,hidyadf,dhidyadf] = MakeATrouFilter(Type,Par)
% Inputs
%   Type   string, one of:
%           'Spline'
%   Par    Par = 3 only
55 %
% Outputs
%   lodyadf    low-pass dyadic filter

```

```

% dlodyadf    dual low-pass dyadic filter
% hidyadf     high-pass dyadic filter
% dhidyadf    dual high-pass dyadic filter
    sqrt2 = sqrt(2);
5    if strcmp(Type,'Spline'),
        lodyadf = [0.125 0.375 0.375 0.125].*sqrt2;
% for Haar
%    lodyadf = [0. 0.5 0.5 0].*sqrt2;
        dlodyadf = [0.125 0.375 0.375 0.125].*sqrt2;
10    hidyadf = [.5 -.5].*sqrt2;
        dhidyadf = [-.03125 -.21875 -.6875 .6875 .21875
.03125].*sqrt2;
    end

15    % Written by Maureen Clerc and Jerome Kalifa, 1997
    % clerc@cmapx.polytechnique.fr, kalifa@cmapx.polytechnique.fr

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%

25

function row = ShapeAsRow(sig)
% ShapeAsRow -- Make signal a row vector
% Usage
30    % row = ShapeAsRow(sig)
% Inputs
% sig      a row or column vector
% Outputs
% row      a row vector
35    %
% See Also
% ShapeLike
%
40    row = sig(:)';

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%

```

CLAIMS

1. A method for reconstructing image data corresponding to a desired two-dimensional image from initial tomographic data associated with a plurality of initial tomographic projections of said desired image, comprising:

5 backprojecting said initial tomographic data to form backprojected image data;

 selecting a vector family to decompose said backprojected image data from the group consisting of 1-D orthogonal wavelet packet basis, 2-D orthogonal wavelet packet basis, 1-D biorthogonal wavelet packet basis, 2-D
10 biorthogonal wavelet packet basis, 1-D wavelet packet frame, 2-D wavelet packet frame, 1-D complex wavelet frame, 2-D complex wavelet frame, 1-D complex wavelet packet frame, and 2-D complex wavelet packet frame;

 decomposing said backprojected image data to generate decomposed coefficients associated with said selected vector family;

15 diagonally operating on said decomposed coefficients to generate modified decomposed coefficients; and

 recomposing said image data corresponding to said desired two-dimensional image from said modified decomposed coefficients.

2. A method for reconstructing image data corresponding to a desired
20 two-dimensional image from initial tomographic data associated with a plurality of initial tomographic projections of said desired image, comprising:

 selecting a vector family to decompose said initial tomographic data from the group consisting of 1-D orthogonal wavelet packet basis, 2-D orthogonal wavelet packet basis, 1-D biorthogonal wavelet packet basis, 2-D
25 biorthogonal wavelet packet basis, 1-D wavelet packet frame, 2-D wavelet packet frame, 1-D complex wavelet frame, 2-D complex wavelet frame, 1-D complex wavelet packet frame, and 2-D complex wavelet packet frame;

 decomposing said initial tomographic data into decomposed coefficients associated with said selected vector family;

diagonally operating on said decomposed coefficients to generate modified decomposed coefficients; and

recomposing said modified decomposed coefficients to generate regularized data associated with a plurality of regularized tomographic projections; and

backprojecting said regularized data to form said image data corresponding to said desired two-dimensional image.

3. A method for reconstructing image data corresponding to a desired two-dimensional image from initial tomographic data associated with a plurality of initial tomographic projections of said desired image, comprising:

selecting a vector family to decompose said initial tomographic data from the group consisting of 1-D orthogonal wavelet packet basis, 2-D orthogonal wavelet packet basis, 1-D biorthogonal wavelet packet basis, 2-D biorthogonal wavelet packet basis, 1-D wavelet packet frame, 2-D wavelet packet frame, 1-D complex wavelet packet frame, and 2-D complex wavelet packet frame;

decomposing said initial tomographic data into decomposed coefficients associated with said selected vector family;

diagonally operating on said decomposed coefficients to generate modified decomposed coefficients;

selectively amplifying said modified decomposed coefficients to generate selectively amplified coefficients;

recomposing said selectively amplified coefficients to generate regularized data associated with a plurality of regularized tomographic projections; and

radially interpolating said regularized data to form said image data corresponding to said desired two-dimensional image.

4. A method for reconstructing image data corresponding to a desired two-dimensional image from initial tomographic data associated with a plurality of initial tomographic projections of said desired image, comprising:

selecting a vector family to decompose said initial tomographic data from the group consisting of 1-D orthogonal wavelet packet basis, 2-D orthogonal wavelet packet basis, 1-D biorthogonal wavelet packet basis, 2-D biorthogonal wavelet packet basis, 1-D wavelet packet frame, 2-D wavelet packet frame, 1-D complex wavelet packet frame, and 2-D complex wavelet packet frame;

decomposing said initial tomographic data into decomposed coefficients associated with said selected vector family;

selectively amplifying said decomposed coefficients to generate selectively amplified coefficients;

diagonally operating on said selectively amplified coefficients to generate modified decomposed coefficients;

recomposing said modified decomposed coefficients to generate regularized data associated with a plurality of regularized tomographic projections; and

radially interpolating said regularized data to form said image data corresponding to said desired two-dimensional image.

5. The method of claim 1, 2, 3 or 4 wherein said diagonally operating comprises thresholding the data operated on.

6. The method of claim 1, 2, 3 or 4 wherein said selecting a vector family step further comprises:

deriving a model of noise present in said data to be decomposed;

repeatedly selecting a wavelet packet decomposition from a predetermined plurality of wavelet packet decompositions;

calculating an estimation of final estimation error based on at least said selected wavelet packet decomposition and said noise model; and

choosing a wavelet packet decomposition that minimizes the estimation of final estimation error calculated in said repeatedly selecting step.

7. The method of claim 6 wherein said calculating an estimation of final estimation error is also based on prior information about said desired two-dimensional image.

8. A method for reconstructing image data corresponding to a plurality of two-dimensional slices of a desired three-dimensional image from initial tomographic data associated with a plurality of tomographic projections of said plurality of two-dimensional slices, comprising:

selecting a vector family to decompose said initial tomographic data selected from the group consisting of wavelet vector family and wavelet packet vector family;

decomposing said initial tomographic data to generate decomposed coefficients associated with said selected vector family;

diagonally operating on said decomposed coefficients to generate modified decomposed coefficients; and

recomposing said modified decomposed coefficients to generate regularized data associated with a plurality of regularized tomographic projections of said plurality of two-dimensional slices of said desired image; and

backprojecting said regularized data to form said image data corresponding to said plurality of two-dimensional slices of said desired three-dimensional image.

9. A method for reconstructing image data corresponding to a plurality of two-dimensional slices of a desired three-dimensional image from initial tomographic data associated with a plurality of tomographic projections of said plurality of two-dimensional slices, comprising:

backprojecting said initial tomographic data to form backprojected image data associated with said plurality of two-dimensional slices;

selecting a wavelet vector family to decompose said backprojected image data;

decomposing said backprojected image data to generate decomposed coefficients associated with said selected vector family;

diagonally operating on said decomposed coefficients to generate modified decomposed coefficients; and

5 recomposing said modified decomposed coefficients to form said image data corresponding to said plurality of two-dimensional slices of said desired three-dimensional image.

10 10. The method of claim 8 further comprising performing slice-by-slice two-dimensional regularization on said initial tomographic data to form regularized data corresponding to a series of regularized two-dimensional slices before said decomposing step wherein said decomposing step is performed on the entirety of said regularized data.

15 11. The method of claim 9 further comprising performing slice-by-slice two-dimensional regularization on said initial tomographic data to form regularized data corresponding to a series of regularized two-dimensional slices before said backprojecting step wherein said backprojecting step is performed slice-by-slice on the entirety of said regularized data

20 12. The method of claim 9 further comprising performing slice-by-slice two-dimensional regularization on said backprojected image data to form regularized data corresponding to a series of regularized two-dimensional slices before said decomposing step wherein said decomposing step is performed on the entirety of said regularized data

13. The method of claim 8 or 9 wherein said diagonally operating comprises thresholding the data operated on.

25 14. The method of claim 8 or 9 wherein said selecting a vector family step further comprises:

deriving a model of noise present in said data to be decomposed;

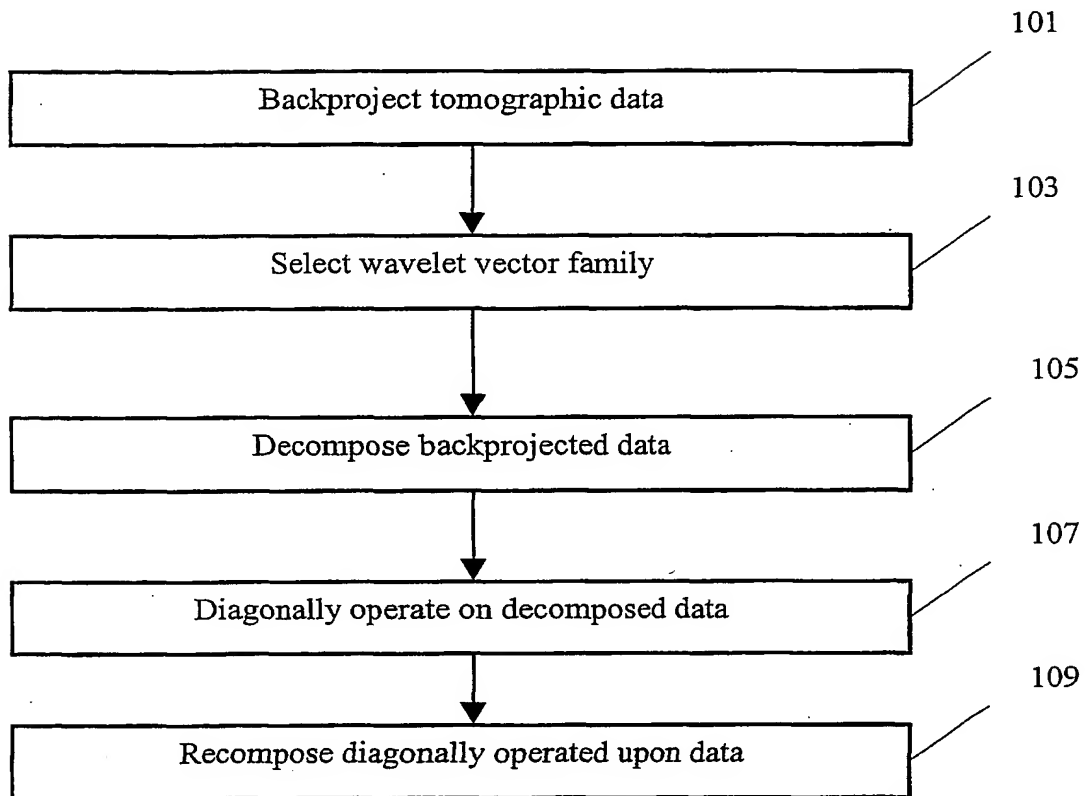
repeatedly selecting a wavelet packet decomposition from a predetermined plurality of wavelet packet decompositions;

calculating an estimation of final estimation error based on at least said selected wavelet packet decomposition and said noise model; and

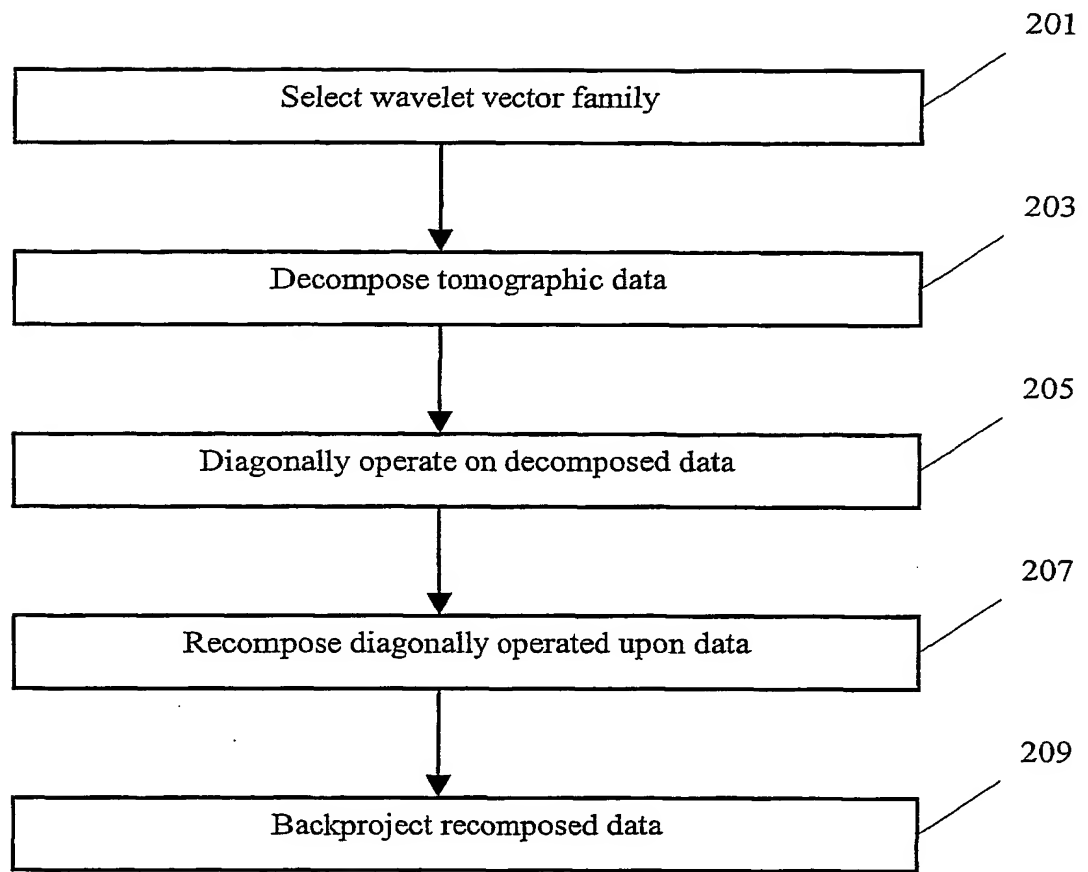
5 choosing a wavelet packet decomposition that minimizes the estimation of final estimation error calculated in said repeatedly selecting step.

15. The method of claim 14, wherein said calculating an estimation of final estimation error is also based on prior information about said plurality of two dimensional slices of said desired three-dimensional image.

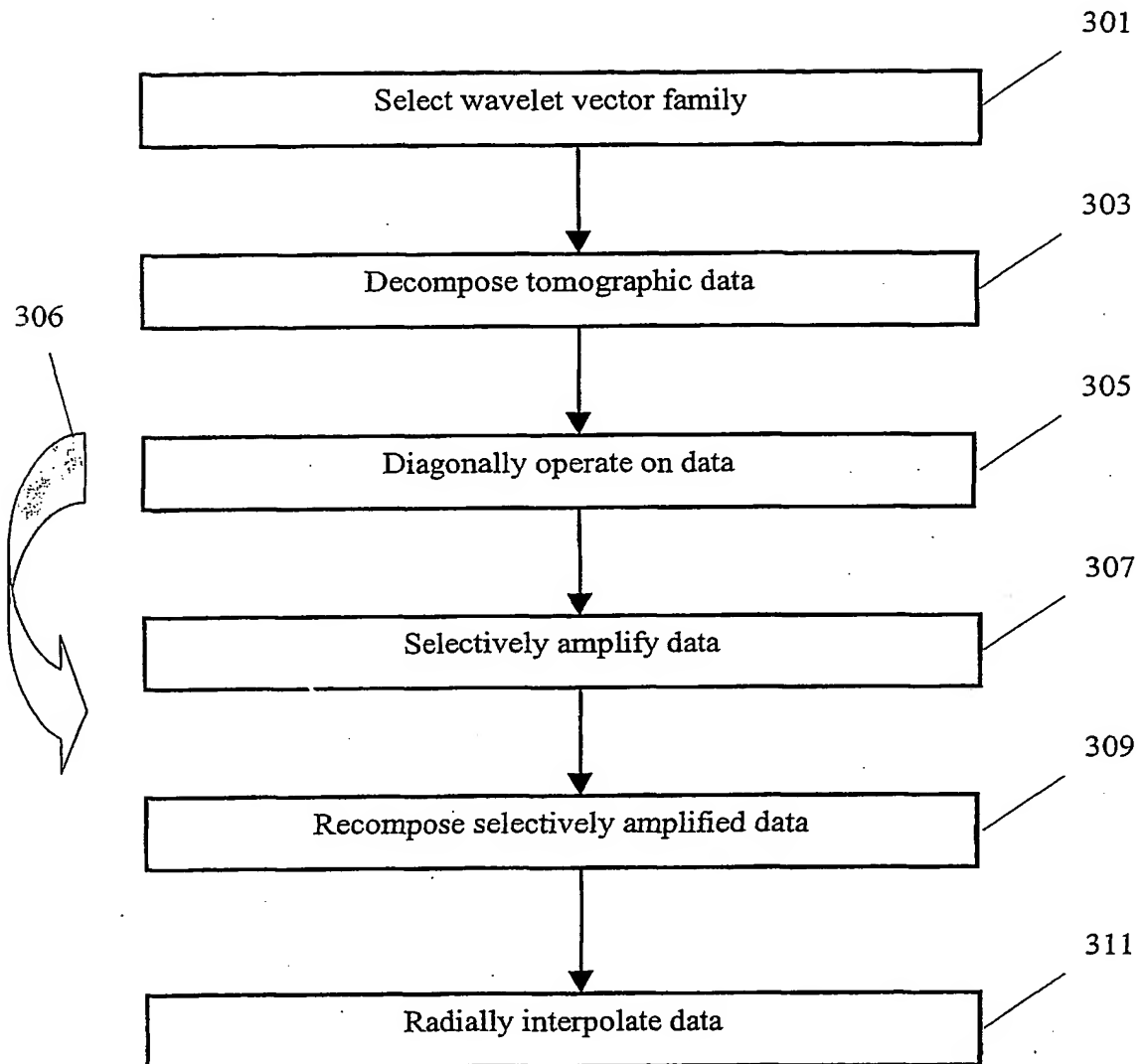
1/5

**Figure 1**

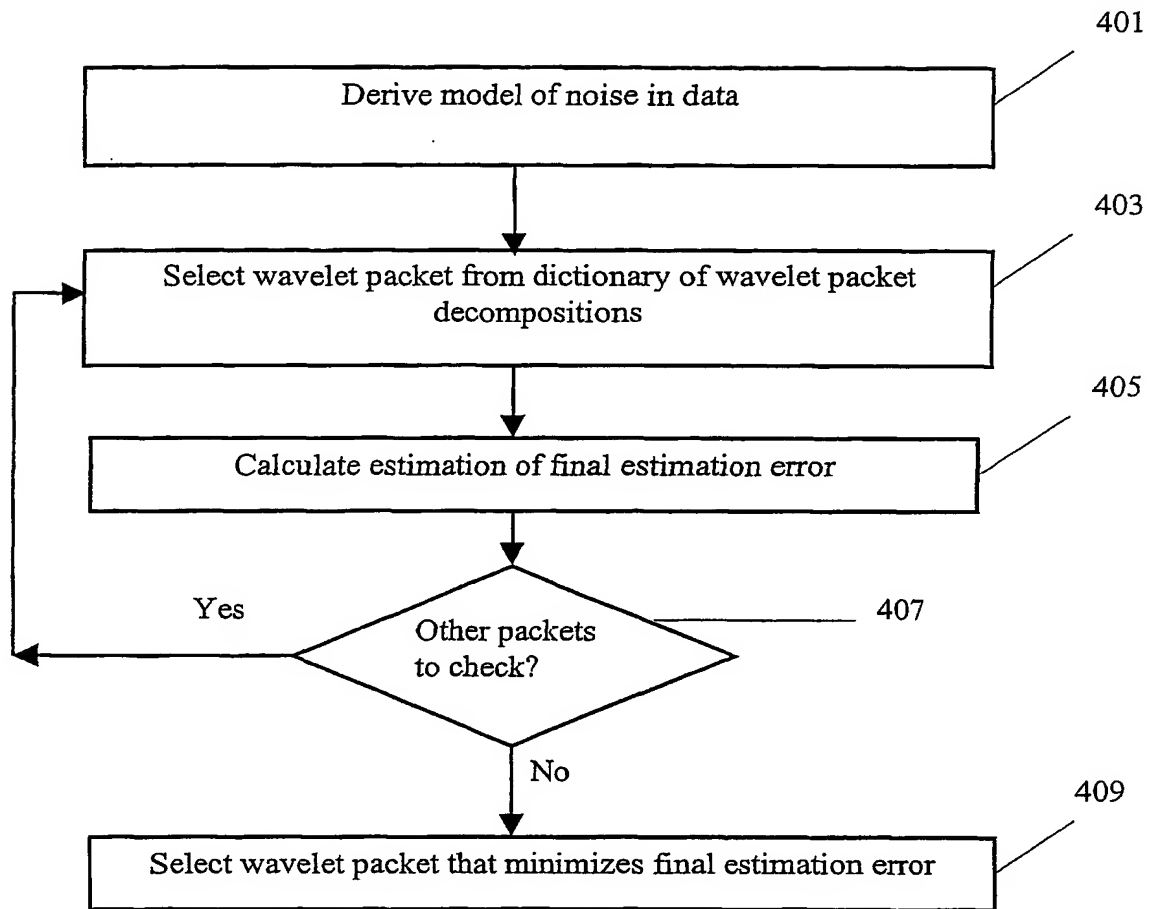
2/5

**Figure 2**

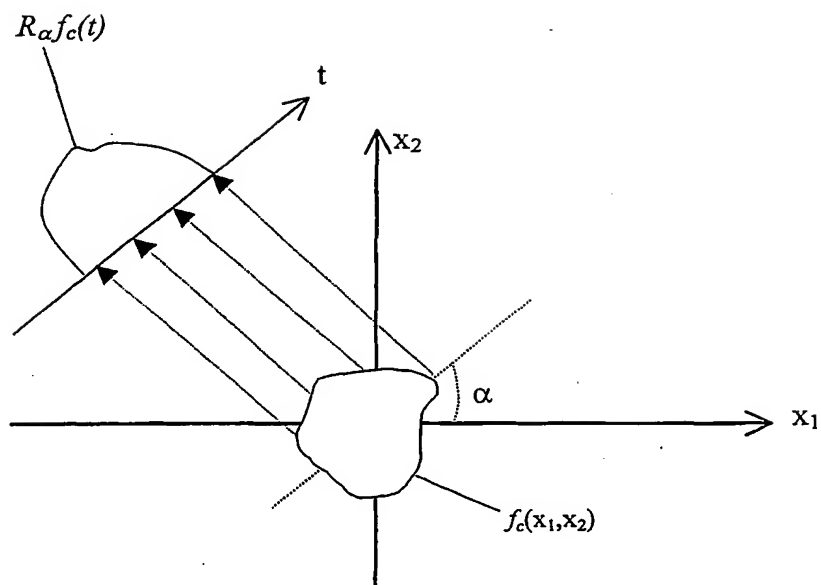
3/5

**Figure 3**

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**Figure 4**

5/5

**Figure 5**

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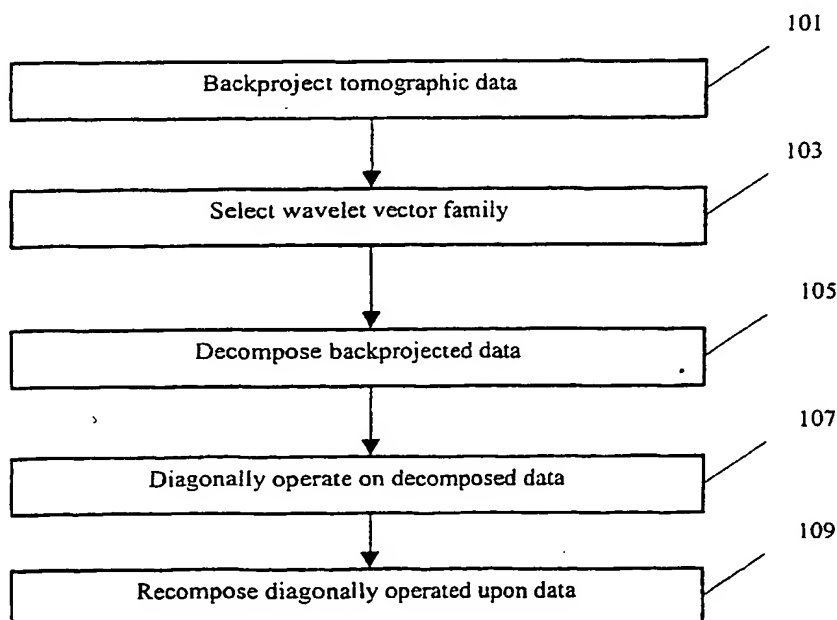
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- (72) Inventors; and
- (75) Inventors/Applicants (for US only): **KALIFA, Jerome** [FR/US]; 184 Thompson Street, New York, NY 10012 (US). **LAINE, Andrew** [US/US]; 39 Claremont Avenue.
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[Continued on next page]

(54) Title: METHOD FOR TOMOGRAPHIC RECONSTRUCTION WITH NON-LINEAR DIAGONAL ESTIMATORS



(57) Abstract: Techniques for tomographic reconstruction using non-linear diagonal estimators are disclosed. In a preferred embodiment, tomographic data from a tomographic device is decomposed in a wavelet vector family. Regularization of the tomographic data is accomplished by performing a thresholding operation on coefficients of the decomposed data. The regularized data is reconstructed into image data that may be displayed. In another preferred embodiment, a wavelet packet vector family is used to decompose the tomographic data. The wavelet packet is selected from a dictionary of wavelet packets using the best basis algorithm.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

INSPEC, EPO-Internal, WPI Data, PAJ, IBM-TDB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	<p>KALIFA J ET AL: "Thresholding estimators for minimax restoration and deconvolution" PROCEEDINGS OF THE IEEE-EURASIP WORKSHOP ON NONLINEAR SIGNAL AND IMAGE PROCESSING (NSIP'99), PROCEEDINGS OF THE IEEE-EURASIP WORKSHOP ON NONLINEAR SIGNAL AND IMAGE PROCESSING (NSIP'99), ANTALAYA, TURKEY, 20-23 JUNE 1999, pages 1-5 vol.1, XP001059678 1999, Istanbul, Turkey, Bogazici Univ, Turkey ISBN: 975-518-133-4 page 2, left-hand column, paragraph 2.1 -page 3, left-hand column, paragraph 3. page 4, left-hand column, paragraph 3.2 -right-hand column, paragraph 3.3 --- -/--</p>	1-15

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

4 February 2002

Date of mailing of the international search report

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel (+31-70) 340-2040, Tx. 31 651 epo nl.
Fax: (+31-70) 340-3016

Authorized officer

Perez Molina, E

INTL NATIONAL SEARCH REPORT

Intern. Application No
PCT/US 01/13737

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5 953 388 A (BERENSTEIN CARLOS ALBERTO ET AL) 14 September 1999 (1999-09-14) column 10, line 13 -column 13, line 1; figures 12-14 ---	1-15
A	KALIFA J ET AL: "Image deconvolution in mirror wavelet bases" PROCEEDINGS 1998 INTERNATIONAL CONFERENCE ON IMAGE PROCESSING. ICIP98 (CAT. NO.98CB36269), PROCEEDINGS OF IPCIP'98 INTERNATIONAL CONFERENCE ON IMAGE PROCESSING, CHICAGO, IL, USA, 4-7 OCT. 1998, pages 565-569 vol.1, XP010308723 1998, Los Alamitos, CA, USA, IEEE Comput. Soc, USA ISBN: 0-8186-8821-1 page 566, left-hand column, paragraph 2 -page 567, left-hand column, paragraph 4 page 568, left-hand column, paragraph 5.2 -right-hand column, paragraph 6. ---	1-15
A	US 5 841 890 A (KRASKE WOLFGANG F) 24 November 1998 (1998-11-24) column 4, line 15 -column 5, line 35 -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 01/13737

Patent document cited in search report		Publication date	Patent family member(s)	Publication date
US 5953388	A	14-09-1999	NONE	
US 5841890	A	24-11-1998	AU WO	3059597 A 9742592 A1
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